The Effect of Fire on Runoff and Soil Erosion
in Royal National Park, New South Wales.

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Declaration of Originality

I declare that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

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March 1997

Note to the reader:

References to company or product names are made in this thesis. These names are supplied for specific information only and no implication or recommendation of the product are made by the author, the CRC for Catchment Hydrology or the Australian National University, to the exclusion of others that may be suitable.

These references are usually depicted by the symbol ®.

Abstract

The January 1994 fires were among the most severe bushfires of this century. Large areas were burned and many lives affected. The extent and severity of the fires evoked a widespread public response. Awareness of the potential scale of bushfires in Australia and the limitations in our capabilities of managing fire and its impacts on life and property reached a new level. There was also growing public concern about detrimental impacts resulting from the fires on the environment.

The fires had also generated interest in the scientific community who realised the opportunity presented by the fires to study ecological and geomorphological processes activated by the extensive burning of native bushlands. Also, the need for reliable data and information in general on the effects of fire in these landscapes and in Australia in general was realised.

This study was developed to investigate some effects of the January 1994 bushfires on runoff and soil erosion processes. An area within Royal National Park, approximately 50 km south of Sydney in NSW, Australia was selected for study.

The project used a combination of field observation and erosion experiments to investigate the generation of runoff and sediment production in an area which was burned by fire of severe intensity. The extent of the fires meant that no unburned control site was available for measurement of background runoff and erosion rate which is recognised as a major limitation of this study.

Observations carried out during preliminary field visits to the study area suggested that there was some sheet erosion occurring on the burned but otherwise undisturbed areas. The soil surface appeared to be resistant to severe degradation by rain- and flow-driven erosion processes. Tracks and trails were showing damage by severe erosion and sedimentation which was attributed to the interception and channelling of sheet flow generated on the burned areas. The presence of a water repellence was noted and observed to be widespread. Several hypotheses concerning processes leading to runoff and erosion were proposed based on these observations which were to be tested by the experimental program.

The hypotheses proposed that fire had resulted in conditions of low cover and induced or enhanced water repellence. These conditions were thought to be most severe immediately after the fire and expected to reduce to pre-fire level with regeneration of vegetation and recovery of the ecosystem as a whole. During the post-fire recovery, soil to erosion was expected to be limited by erosivity of rainfall and runoff and soil erodibility, which was expected to be low based on the field observations.

The hypotheses also propose that while the fire has increased runoff and erosion, the resistance of the soil is sufficient to prevent degradation of the soil from erosion resulting from rainfall and runoff events under average climatic conditions and that extreme events would be required to cause a significant increase in erosion rate. Also proposed is that the regeneration of soil cover would lead to a reduction in runoff generation and erosion, and that the level of water repellence would be reduced as a result of biological activity of the soil.

The experimental program used erosion plots of 5 % slope and simulated rainfall events of intensity and duration ranging from less than 1 in 1 year to that approaching a 1 in 100 year return period to study the effects of rainfall intensity on runoff and sediment production 4 months and 28 months after the fire. The effect of water repellence on runoff and soil erosion were also examined using a comparison between plots in their natural, hydrophobic state with plots treated with a wetting agent.

The experimental work showed that the burned, but otherwise undisturbed soil surfaces were quite resistant to erosion and sediment production was low, reaching a maximum of $0.67 tha^{-1}$ for 49 mm of rain applied in 20 minutes. Soil cover which increased from an average of 56% at 4 months after the fire to 74% at 28 months, had no effect on runoff and sediment production. While sediment concentration was apparently unrelated to rainfall and discharge characteristics, there were strong relationships between sediment yield and rainfall, and sediment yield and runoff.

Conversion of rainfall to runoff on the fire affected areas was found to be high; mean runoff expressed as a percentage of rainfall ranged from 38% to 68% for the rainfall intensities applied. Water repellence was found to be a dominant factor in the runoff generation process by limiting the infiltration of rainfall. Comparison of natural, water repellent soil surfaces with plots treated with wetting agent indicated that without the effect of water repellence, mean runoff as a percentage of rainfall was significantly less, ranging from 4% to 52% for equivalent rainfall intensities. Since sediment production was linked to runoff, water repellence also had a significant effect on sediment yield.

These results indicate that there were no significant changes in runoff and sediment production between the first set of experiments at 4 months and the second set at 28 months after the fire. The post-fire recovery process in this environment is thus expected to require more time before runoff and erosion declines to its pre-fire level. An alternative explanation could be that the fires actually did not change runoff and erosion processes although this possibility is considered to be remote.

The erosion response is considered to be low on the conditions tested and level of simulated rainfall applied. The literature indicates that severe wildfire followed by large rainfall events can result in catastrophic erosion in the form of flooding and debris flows on a catchment scale and severe sheet and rill erosion on a hillslope scale. This was not observed in this case. The low level of erosion observed is attributed to the combination of low slope and a highly resistant soil surface.

The high runoff coefficient due to the soil water repellence observed at the plot level is believed to have the effect of increasing runoff at hillslope and catchment level. This effect raises the potential for erosion by flows and could result in flooding. The degradation of tracks and trail observed are believed to such a response.

The coastal heathland and forest-terrace landscapes examined appear inherently resistant to soil erosion due to their morphology. Our experiments have showed that the heathland soils on the gentler slopes are quite resistant to erosion by rain-driven processes. Our observations suggest that the litterdams and microterraces have an important role in spreading flows in the heathland areas and therefore limiting erosive forces to rain-driven processes on these slopes. Qualitative investigation of the bench terraces which form the steeper slopes suggest that this environment is protected from accelerated erosion due to high ground cover and the nature of the rock formations.

These findings indicate that the installation of broadscale post-fire erosion control measures is not warranted in this environment. Additional consideration of the ecological implications of such measures in an area of high conservation value render the treatment of burned but undisturbed areas as inappropriate. Control measures should be targeted at areas subject to degradation due to additional disturbance such as tracks and trails.

Acknowledgments

When I wrote my Honours thesis, I thanked my then girlfriend, now wife, Michelle as last but definitely not least contributor to my work. I remarked that I cherished her support and encouragement above all. A lot of things have happened since then but not much has changed in that regard, Michelle is still understanding, encouraging and supportive. Thank you Michelle, I finished this work for us.

Every honours and postgraduate student I know (almost every anyway) has faced adversities during their respective projects. The people involved in this project and those unfortunate enough to be around me at the time know that I had my share of them as well. I think no one would have blamed me if I hadn't finished this work . Thinking back though, there are so many people who have helped me out, especially when things got tough, that I owed it to them as much as to myself. Some of these people are listed below.

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Chapter 1

Introduction

1.1 Introduction

Fire has been an integral part of the environment for millions of years. As such, it has been a major force in the evolution of our present landscapes. Fire can affect a range of physical, chemical and biological processes in the soil-plant system and its interactions with the atmosphere. Some of these traits have been exploited by humans who have used fire not only as a source of warmth and as a weapon but also as a land management tool.

Fire can also be a threat to human life and possessions. The suppression of large scale fires is frequently impossible due to the rate of spread and intensity of the fire. In order to avoid such events or at least minimise their occurrences, fuel reduction by using controlled burning is commonly employed as a management tool. Due to the magnitude of the threat of fire, primary consideration is given to fire management while other environmental aspects such as ecology and impact on soil generally receive a lower priority.

Land degradation resulting from anthropogenic activities is putting our present environment under great pressure. Vegetation, soil and water resources which are essential to our existence are particularly threatened. Increasing awareness of our responsibilities as stewards of these resources has lead us to closely examine our land management practices to reduce detrimental impacts that may lead to degradation. Many types of land degradation are natural processes which our activities have changed in some way. Accelerated soil erosion, for example, is an immense problem. While erosion is an important natural process in the long term as it is part of a geomorphological cycle, human activities such as agriculture, mining, forestry and urban development have greatly increased the rate of erosion. Because the rate of soil erosion today greatly exceeds the rate of soil formation we are in danger of depleting one of our most valuable resources.

The impact of fire on land degradation is more difficult to define. The role of fire in landscape evolution revolves around the frequency and severity of fire, ie. the *fire regime*. Single fires have been of relatively low importance in the natural environment. However, many of today's landscapes are already under pressures from other agents related to anthropogenic activities. The impacts of even single fire events are therefore likely to differ to those that would be apparent in a pristine environment.

Frequently, the management of fire, or rather the attempted suppression of life and property threatening fires, revolves around reducing individual large events by substitution with many smaller fires. This change in fire regime is likely to impact landscape processes more severely than a near natural fire regime in a non-pristine environment.

Many environments such as agricultural and pastoral landscapes are heavily modified and fire no longer has the same interaction with the vegetation as it did before the original vegetation was cleared. In managed or unmanaged forests, remnant bushland reserves and national parks, fire still has a major role in the continuing evolution of the local environment. Apart from forestry, the main land use in these areas is for recreational purposes. This can put substantial pressures on these lands which are often on steep slopes and shallow soils - frequently the reason why they have not been claimed for agriculture or development. Yet we often rely on the integrity of these areas as pristine water supply catchments. Some of these landscapes represent unique environments which are often fragile environments of limited distribution such as the alpine areas of the Snowy Mountains. These landscapes are today managed to ensure the conservation of these resources.

Most of these lands are on rugged terrain which makes access difficult for management purposes including fire suppression activities. These areas are prone to burning and still subject to natural wildfires as well as some control burning. Such areas are therefore often viewed as hazards for the development and spread of fire but are also under threat of degradation. The threat of degradation can result both from the side effects of fire on areas already under pressure such as the erosion of tracks and the loss of the natural role of fire in maintaining the ecosystem processes such as nutrient cycling and vegetation succession.

In these areas a balance must be reached by which we avoid the effects of devastating fires on human life and culture, yet preserve the integrity of the landscape which includes fire and the many functions it has.

In order to evaluate and predict the impact of fire on today's environments we must first understand the interaction between fire and landscape evolution processes. Only then can we begin to manage fire and landscapes in such a way that the environment does not degrade.

The interaction between fire and landscapes include many facets, most of which are intricate and quite complex. In this study, the emphasis is on the interaction of fire with soil erosion processes and hydrology. Some related issues of ecology, soil chemistry and soil biology are briefly eluded to in order to provide relevant background information.

1.2 Scope of the Study

In January 1994, many areas in New South Wales and some other states were subjected to some of the most severe bushfires ever witnessed in Australia. The socio-economic impacts were tremendous both in terms of losses of human life and damage to property. Public response to the following bushfire appeal, both nationally and internationally, was immense. The scale of the fires was considerable and a large number of people were affected as the fires passed through bushland adjacent to some of the most heavily populated areas in Australia. For these reasons, the fire resulted in a level of public awareness and concern rarely achieved before. This concern meant that the government agencies responsible for managing the areas affected most severely by the fires, ie. National Parks and remnant bushland reserves, were under pressure to repair the damage.

Consultation and collaboration among these agencies, research organisations and universities were conducive to identifying what approach was needed and what actions should be taken. In many cases, such as Royal National Park, natural recovery was clearly the best strategy. The action taken by the National Parks and Wildlife Service was therefore to exclude the public for safety reasons and to allow the bushland to recover unhindered.

As well as a reviewing management options, gaps in our current knowledge were identified. The opportunity for research presented by the fires was also realised and a study, targeted at some of the knowledge gaps which had been identified, was initiated.

This study was therefore an opportunistic project set up after the January 1994 fires and was designed to use a bushfire affected landscape to provide measurements of erosion processes during the recovery period. The experiments had to be confined to a single location in Royal National Park for logistical reasons but it was anticipated that the findings of the study could be applied to other areas with similar landscapes.

1.3 Main Aim and Objectives

The main aim of the study is therefore to investigate the effect of fire on the generation of runoff and soil erosion processes by water. The objectives of this project, based in the north-eastern part of Royal National Park are to:

1. to examine the effects of fire on soil properties which determine the infiltration of water and the resistance of the soil to erosion,

2. to review the erosion and runoff responses triggered by fire in landscapes subject to burning,

3. to study the potential for erosion and runoff to occur in a fire affected landscape,

4. to study the extent of post-fire recovery during the first 2 years following a severe wildfire, and

5. to identify management options for mitigation of any detrimental effects of erosion following fire.

1.4 Issues Identified and Tested by the Field Study

Using these objectives and initial field observations (described in Chapter 3), the following issues were identified and hypotheses were developed which could, in part at least, be tested with the resources available in this study (these are reproduced here from Section 4.1);

1. areas that were burned but otherwise undisturbed showed signs of overland flow and sheet erosion but rill erosion was observed only rarely,

2. tracks, trails and similar areas showed signs of severe degradation by rill and gully erosion and sedimentation, and

3. using Water Drop Penetration Time and ethanol testing (Crockford *et al.*, 1991), water repellence at the soil surface was shown to be very extensive and severe in all areas other than moist drainage lines and depressions.

These observations were made following natural rainstorms. The intensity or duration of the rain events were unknown but discussion with park rangers indicated that no severe falls had been witnessed. These observations lead to the following hypotheses:

1. The natural, post-fire soil surface is resistant to erosion and incision by raindrop impact and overland flows produced by patterns of average rainfall in this environment. Extreme rainfall events (say with recurrence intervals of greater or equal to 100 years, ie. 110 mmh^{-1} for 30 min in this area) are required to initiate severe degradation of the fire affected soil surface in this landscape.

2. The generation of sheet flow has been changed by the fire due to the loss of soil cover and reduction in infiltration rate.

3. Regeneration of plant cover will reduce the rate of overland flow and soil loss.

4. The interception of sheet flows generated on the fire affected areas by tracks results in catastrophic erosion.

5. The effect of water repellence on infiltration has been altered by the fire. Regeneration of plant cover, accumulation of litter and breakdown of hydrophobic substances will reduce the effect of water repellence over time.

The experiments described in Chapter 4 were designed to test hypotheses 1., 2., and 3. and provide some baseline data on runoff and erosion rates for the study area and similar landscapes which would assist in evaluating hypotheses 4. and 5.

1.5 Chapter Plan

This thesis addresses the aim and objectives outlined above in the following manner:

CHAPTER 1 introduces the topic and the project. This chapter gives broad context for the study which leads into the specific issues this project has attempted to cover. The main aim and detailed objectives are listed here and the thesis structure is outlined.

CHAPTER 2 provides background of erosion processes and reviews the effects of fire on soil properties including soil cover as they relate to the generation of runoff and erosion by water. This chapter also examines types of fire and their implications on landscape development as well as the range of hydrologic and erosion responses reported by other researchers.

CHAPTER 3 gives some background of the circumstances resulting from the fires, provides a brief description of the locality of the study site and describes some observations made following several visits to the area.

CHAPTER 4 describes the experimental study which was undertaken as part of this study. This consisted of two sets of erosion plot experiments in the north eastern part of Royal National Park which was burned by a severe wildfire in January 1994. The experiments were carried out during May 1994 and May 1996 and tested the effect of soil water repellence, soil cover and rainfall intensity on runoff generation and erosion potential.

CHAPTER 5 provides the results of the data sampling and processing from these experiments. The results of the statistical analysis of the data using primarily ANOVA techniques is also given.

CHAPTER 6 discusses the results of the data analysis. This section also attempts to provide a comparison between the results from this study and those reported in the literature. This chapter provides a discussion of the implications of fire for erosion and runoff generation and considers which management options are most appropriate for mitigating potentially detrimental effects of post-fire erosion on the environment.

CHAPTER 7 lists the conclusions drawn by the study and evaluates the hypotheses developed by the study. This chapter also examines the implication of the research for management, identifies further gaps in knowledge of fire-related runoff and erosion processes and suggests possible directions of future research.

Chapter 2

Background and Literature Review

2. Background and Literature Review

The first part of this literature review briefly introduces the processes of soil erosion and defines some of the terminology used. The second part examines the impact of fire on the environment, especially relationship between soil and vegetation cover within landscapes and how this affects landscape geomorphology. The third part introduces some aspects of fire behaviour and implications for management. The final part focuses on the effects of fire on soil and hydrology and reviews the erosion responses observed by other researchers.

2.1 Processes of Soil Erosion

Soil erosion is the physical removal, transport and deposition of soil. The energy required to dislodge soil and move it elsewhere may be supplied by a range of forces, the most common being water and wind.

Soil erosion is an important natural process in shaping and rejuvenating the earth's surface over geologic time scales. Human activities have resulted in accelerated erosion which is in most cases detrimental to the environment. Accelerated erosion of soil leads to a decline in productivity of the soil and off site impacts such as sedimentation and pollution of waterways.

2.1.1 Soil Erosion by Water

In Australia, the most widespread and significant forms of erosion are driven by wind and water (Rosewell *et al.*, 1991). This study focuses on soil erosion processes driven by water, namely rainfall and overland flow.

Soil erosion by water is a complex process and involves many factors. These factors are often interrelated and variable, both in time and space. Essentially the process of soil erosion involves the detachment of soil particles in one location, its transport to another and its deposition. The processes of detachment and transport require energy. This energy is provided by water in the form of rain and overland flow.

Raindrops gravitating to the soil surface and hitting it carry a significant amount of energy. Rosewell (1985) demonstrated that rain falling at an intensity of 50 mmh^{-1} for 30 minutes generates a sufficient amount of energy to raise an equivalent mass to the top 10 cm of soil to a height of 45 cm. The energy characteristics of water in its various forms which is applied to soil during the erosion process is also called *erosivity*. Whether or not the applied energy causes detachment depends on the resistance of the soil, called *erodibility*, and other variables such as soil cover, land management and slope.

Overland flow can also generate significant levels of energy. If the flowing water is spread more or less evenly over a planar surface, the flow is called *sheet flow* and the resulting erosion is termed *sheet erosion* or *interrill erosion*. Sheet erosion is important because it affect a large surface area and degrades the surface of the soil. The soil surface is the interface of the soil with the atmosphere. The state of the soil surface is important as it controls the rate of exchange of air and water between soil and atmosphere (Hillel, 1980). Water supplied to the surface by rain or flow needs to infiltrate through the surface to enter the soil. Often the rate of infiltration is limited because of degradation by raindrop impact. This form of degradation is called surface *sealing* or *crusting* (Bradford and Huang, 1992; Bradford *et al.*, 1986; McIntyre, 1958). Crusts are formed by a combination of compression by raindrops and infilling of pores by small particles detached by raindrop impact. When the rainfall rate exceeds the capacity of soil to infiltrate the water, the water begins to collect, or *pond*, at the surface. Depending on slope and microtopography, the water begins to flow, or *run off*, initially as small pulses and once sufficient water has accumulated, as a continuous flow. This is called Hortonian overland flow or simply *runoff*.

The combination of rainfall impact and sheet flow is sometimes referred to as *rain-flow* (Kinnell, 1990; Singer and Walker, 1983; Moss *et al.*, 1978). In this type of erosion, the impacting raindrops create additional turbulence and energy to the flow. The flow acts as a transport medium for detached soil particles while the impacting drops provide bursts of energy to detach particles and role them along in the flow. Moss *et al.* (1978) showed that rain-flow erosion was capable of eroding surfaces at a greater rate than flow or rain impact alone. They pointed out that raindrop impact alone may detach soil but is in-efficient in transporting the detached soil. The transport of soil by rain alone is dependent on repeated impacts moving the soil particles short distances until they are hit by raindrops again. This action is commonly referred to as *saltation*. Shallow overland flow is often *detachment-limited*, ie. it is more efficient at transporting detached, loose particles of soil and litter than it is at detaching these from the soil surface (Moss *et al.*, 1978). Moss and Green (1983) showed that the depth of flow is very important in this process. In their experiments they showed surface water can have an attenuation effect on raindrop impact. The level of protection of the surface depends on the ratio of drop size to water depth and becomes complete when the water depth reaches 3 times the diameter of the drops.

Rain impact on shallow overland flow also tends to ensure that the flow remains spread out over a plane (Singer and Walker, 1983). When depth of flow increases to the point where rain impact has little effect, flow starts to concentrated in topographical lows or *drainage depressions*. On very rough surfaces such as ploughed fields, the micro-topography dominates from the beginning of runoff.

The concentration of flow in drainage depressions can lead to a different form of erosion. When the energy of the flow becomes sufficient, concentrated flow of water can excavate channels. This type of erosion is called *rill erosion* or *gully erosion* (Hudson, 1986). Gullies are channels that are at least 30-50 cm deep, ie. they are not removed by conventional tillage practices. The energy of the flow depends on a number of factors including the volume of the flow and the slope of the land (which influences flow velocity). Again, a number of factors influence whether the detachment process is successful. The flow needs to apply enough force to the surface to detach particles. The force exerted on the surface by flow is mostly friction and is measured as *shear stress*. Shear stress depends greatly on the area of contact between water flow and the soil, or the *wetted perimeter*. When flow becomes concentrated in a drainage depression, the depth and hence the energy of flow increases while the wetted perimeter is relatively small (when compared to sheet flow). This leads to a concentration of shear stress which may detach soil if its resistance is sufficiently low. Once flow has successfully detached soil along the length of a drainage depression, a *rill* has been incised. This leads to further concentration of flow and later runoff events will erode these further unless the rill is removed or stabilised in some way.

Rill and gully erosion are important because they can detach and transport large quantities of soil. This type of erosion is usually *transport limited* because the large volume of water can *entrain*, ie. pick up and carry along, sediment not as quickly as the soil is detached by collapse of the sidewalls of the rill of gully. Recently tilled paddocks are very erodible as the soil is loose and may also be subject to transport limited rill erosion because of the sheer volume of sediment available may be more than small channels can carry (Hudson, 1986).

Soil texture and structure has an important effect on the soil erosion process. Soil structure, which includes properties such as *aggregation* and strength, gives the soil resistance to erosion. Aggregation of soil is the cementing of primary soil particles by clays and organic substances into larger particles called aggregates. The way in which these aggregates fit together, including the gaps between the aggregates, is called soil structure (Hillel, 1980). Soils with poor structure and aggregation such as coarse textured soils and sands are not very cohesive and provide little resistance to erosion. They are said to be highly erodible (Hudson, 1986).

The gaps between the solid soil matter are called *pores*. Structure also determines the amount of pores in the soil and how they interconnect, described as *porosity*. The porosity of soil is important as it affects the flux of air, water and roots through the soil. A very porous soil has a lot of pathways for water to infiltrate which reduces the chance of erosion by water because only intense rainfall will result in ponding and runoff. Highly organic soils, which are rare in Australia, or coarse textured soils have a high porosity. *Macropores* are channels in the soil caused by burrowing animals such as earthworms and spiders or the remnant of decayed plant roots, and can conduct a large volume of water (Hillel, 1980) and are easily visible to the naked eye. Macropores can therefore perform an important function in improving infiltration of water into the soils and providing drainage to reduce waterlogging.

Vegetation and other cover, such as leaf litter, sticks and pebbles can play an important role in the erosion process. Soil cover can protect the soil surface from raid-driven and flow-driven erosion. Cover protects the soil either directly by shielding the soil or indirectly by retarding runoff.

2.2 Fire and the Environment

Fire is a phenomenon that occurs naturally in almost all continents and their landscapes. Fire occurs more frequently in arid areas than in moister climates. The extent to which fire can contribute to the shaping a landscape is influenced by the types of fire, its frequency and severity, as well as seasonal effects; commonly referred to as the *fire regime* (Gill *et al.*, 1981, Gill, 1975).

Areas which have periodic dry spells are more prone to burning and have evolved to possess distinct vegetation, hydrology and weathering regimes (Moreno and Oechel, 1994; van Wilgen *et al.*, 1992; Booysen and Tainton, 1984; Gill, 1981b; Gill, 1975; di Castri and Mooney, 1973). These environments include Mediterranean-Type Ecosystems (di Castri and Mooney, 1973) such as the forests and scrublands in the Mediterranean, the *Chaparral* in California and the South African *Fynbos*, Sage Brush Communities (Simanton *et al.*, 1988), Pinyon-Juniper Woodlands in North America (Klopatek *et al.*, 1988), Aleppo Pine Forests in the Middle East (Kutiel, 1994; Kutiel *et al.*, 1990), and practically all of Australia (Gill, 1975).

2.2.1 The Relationship of Fire and Vegetation

The component of a landscape most immediately affected by burning is its vegetation. Gill (1975) points out that while plant species cannot adapt to fire *per se*, they can adapt to a fire regime via adaptive traits such as survival or reproductive cycles. The fire regime of a landscape can therefore have an important role in the evolution of its vegetation type.

Gill (1975) describes fire as a unique environmental variable due to its self propagating nature, short term occurrence in any one location, potentially devastating effect and wide distribution across a range of environments and plant communities. In this review, the author classifies fire as a *third order* environmental variable (Figure 2.1). Light, air, solar heat, water and nutrients are *first order* variables on which the existence of plant life depends. Vegetation forms the *second order* variable while fire and herbivorous organisms, which depend on plants form *third order* variables. The two are distinct in that fire is inorganic or *abiotic*. Carnivores are of lower order still, depending in turn on the graziers.

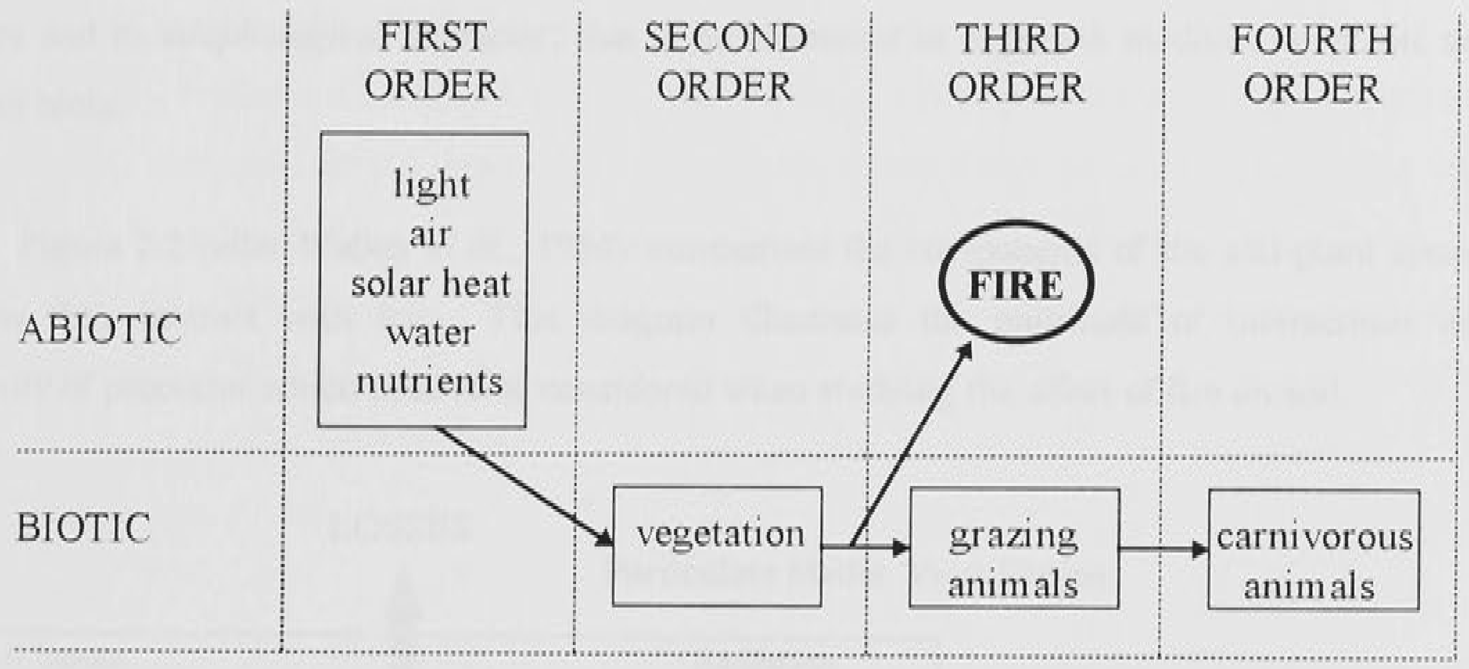


Figure 2.1 (after Gill, 1975); Illustration of the position of fire among relationships between some ecosystem components: for each arrow read "...in natural habitats are necessary for the presence of...".

Gill (1975) has thus illustrated the dependence of fire on plant material. He points out that extremities of first order environmental variables such as drought, floods, cyclones and frosts can dramatically effect vegetation in a similar manner to fire but because of their independence, these do not form the same relationship.

2.2.2 Fire and Soil Formation

Soil can also be directly affected in the combustion process but in comparison to the life cycle of plants, impacts of fire on soil formation processes or *pedology* are more difficult to detect as Walker *et al.*(1986) point out. As these authors discuss, the difference in time scales is vast - fire is transient and episodic by nature while the process of soil formation is long term. The high level of spatial variability in biological, chemical and physical soil components also contributes to the complexity of quantifying fire-soil interaction.

Walker *et al.* (1986) point out that in order to identify true change in soil character as opposed to detecting oscillations, it is necessary to carry out measurements over several climatic events and to identify past fire effects. This is because the measurement of soil processes before and / or after fire represent the net effect of many dynamic and interactive processes and the isolation of effects imparted by fire alone is difficult.

As discussed by these and other authors (Clinnick, 1984; Humphreys and Craig, 1981; Debano *et al.*, 1979; Wells *et al.*, 1979; Debano *et al.*, 1977), the effect of fire on soil properties includes chemical, physical and hydrological aspects which in turn affect the soils pedological character and its *edaphological* character; that is its behaviour as a growth medium for plants and other soil biota.

Figure 2.2 (after Walker *et al.*, 1986) summarises the components of the soil-plant system and how they interact with fire. This diagram illustrates the multitude of interactions and complexity of processes which need to be considered when studying the effect of fire on soil.

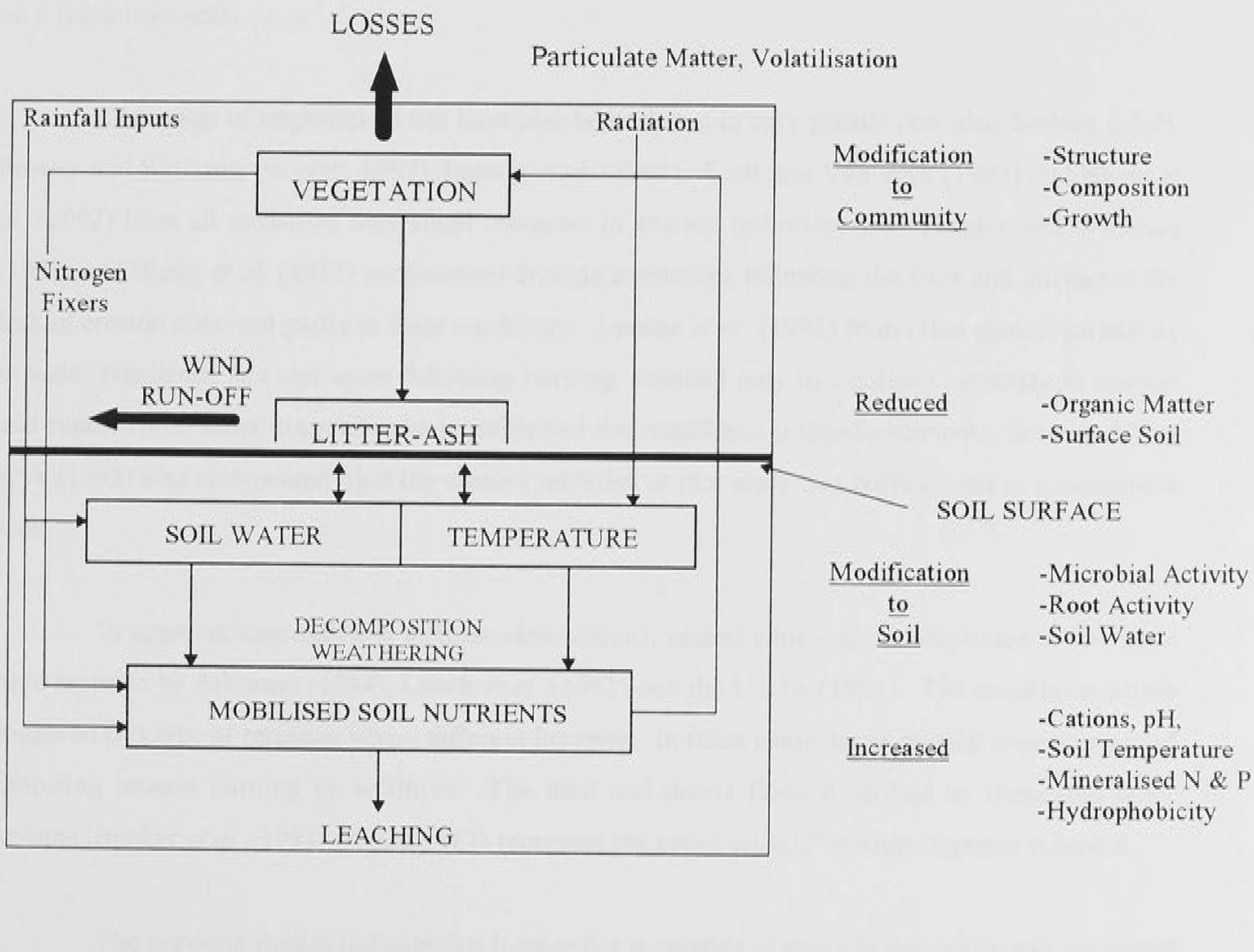


Figure 2.2 (after Walker *et al.*, 1986); Summary of possible interactions in the soil-plant environment during and following fire.

2.2.3 The Effect of Fire on Landscape Geomorphology

Landscapes form through processes of weathering, erosion and deposition (Twidale, 1968). Fire affects these processes by influencing the soil cover and roughness (Lavee *et al.*, 1995; Greene *et al.*, 1990; Debano *et al.*, 1979), composition of the vegetation (Daly and Hodgkinson, 1996; Kutiel, 1994; Gill, 1975) and the dynamics of the soil-plant system (Walker *et al.*, 1986; Debano *et al.*, 1977).

Fire accelerates the rate of weathering and erosion in several ways and on a range of scales. Christensen (1994) states that exposed parent rock is subjected to accelerated weathering due to heat-caused spalling. Debano *et al.* (1979) describes how fire can result in reduced infiltration of rain and increased runoff through a combination of fire-induced water repellence and surface sealing by rain splash. The increased rate of runoff can then lead to increased erosion. Several authors (Emmerich and Cox, 1994; Diaz-Fierros *et al.*, 1990; Prosser, 1990; Blong *et al.*, 1982 and others - see Section 2.3.7) have measured increases in erosion from burned plots while other studies (Scott and Van Wyk, 1990; Leitch *et al.*, 1983 Good, 1973; Brown, 1972) measured increases in water and sediment yield on a catchment scale.

The range of responses to fire have also been shown to vary greatly (see also Section 2.3.7). Prosser and Williams (in prep. 1997), Imeson *et al.* (1992), Scott and Van Wyk (1992) and Blong *et al.* (1982) have all measured only small increases in erosion following fire. Prosser and Williams (1997) and Blong *et al.* (1982) encountered drought conditions following the fires and attributed the lack of erosion observed partly to these conditions. Imeson *et al.* (1992) found that spatial variability in water repellence and soil cover following burning resulted only in localised increases in erosion and runoff while other areas effectively infiltrated the runoff and trapped sediment. Scott and Van Wyk (1992) also commented that the erosion recorded at plot scale was buffered out at a catchment scale.

In apparent contradiction to these observations, catastrophic erosion responses to fire have been reported by Atkinson (1984), Leitch *et al.* (1983) and the USDA (1954). The conditions which triggered this type of response where different however. In these cases, large rainfall events occurred following intense burning by wildfires. The mud and debris flows described by these and other authors (Booker *et al.*, 1993; Wells, 1987) represent the upper scale of erosion response recorded.

The previous studies indicate that intense fire is capable of severely degrading soil cover and soil surfaces to the extent that severe erosion can occur. Prosser (1990) concluded that mild to moderate burning by Australian Aborigines probably did not cause accelerated erosion because the severity of these burns did not severely affect the soil surface. This was supported by flume experiments undertaken by Prosser and Slade (1994) who found that severe degradation of vegetation and soil surface was required before channel (rill or gully) erosion could be initiated by flow.

Prosser and Winchester (1996) discuss the initiation of channels which has led to widespread gully erosion in eastern Australia, pointing out the required conditions for these geomorphological cycles to be triggered. While the present cycle of gully erosion is attributed to modern farming practices (Prosser and Winchester, 1996), stratigraphic studies of valley-fills indicate episodic gully erosion during the Holocene (Prosser *et al.*, 1994).

Prosser and Winchester (1996) discuss that pre European gully erosion must have been a result of levels of disturbance comparable to that observed in post European culture, as indicated by the flume experiments but point out the difficulty in resolving the processes of initiation given the lack of evidence collected to date. The experiments of Prosser and Slade (1994) have shown that changes in catchment hydrology due to long term climatic fluctuations are unlikely to the be the cause. Severe droughts may have been a factor, as vegetation would have been affected both by lack of water and increased grazing pressure from endemic species. Destruction of vegetation by population explosions in pests such as plague locusts is another possibility. Severe fire is a likely explanation as it has been observed as capable of degrading the soil surface sufficiently for incision to occur (Good, 1973; Lamy and Junor, 1965).

2.2.4 Fire in the Australian Landscape

The history of fire in Australia, especially with regard to changes in fire regime following colonisation of the landscape by Aboriginals and later European settlers, has been well documented in Gill *et al.* (1981). Kemp (1981) points out that before human settlement, fire was relatively infrequent compared to the frequency we observe today. Luke and McArthur (1978) explain that the development of fire requires the coincidence of several environmental variables as well as a source of ignition which, before human intervention was predominantly lightning (Kemp, 1981).

Fire has nevertheless played a major role in the evolution of the Australian Landscape (Singh *et al.*, 1981; Gill, 1975). Singh *et al.* (1981) describe the influence of fire as being *inescapably interwoven with the early evolutionary history of the flora and climate of this region.*

Nicholson (1981) has documented history and importance of fire in the way of life of Australian Aborigines, who used fire as a land management tool. The intentional use of fire resulted in a change of fire regime following human settlement which influenced the evolution of the landscape from then on (Singh *et al.*, 1981).

Gill (1981a) describes further changes in fire regime and land use following European settlement of Australia. This author points out that while fire was probably the major land management tool for Australian Aborigines, fire was only one of many tools which Europeans used to alter the landscape for their purposes.

The changes in the Australian landscape resulting from modern land management practices have been extensive. While fire still plays an important role in the dynamics of many remnant natural systems (Good and Bowden, 1996; Good, 1981) and the management of others (Leigh and Noble, 1981; Shea *et al.*, 1981), the impact of fire is considered today in view of how it affects humans and their possessions. In many instances, fire represents a potential threat to life and property (Luke and McArthur, 1978). This view is reflected in the NSW Bush Fires Act 1949 No. 31 which requires councils and individuals to prevent fire to occur or spread:

> *"...to remove, burn or destroy any inflammable matter or other material upon such land where the council is satisfied that the removal, burning or destruction thereof is necessary for the prevention of the outbreak, spread or extension of a bush fire or other fire."*
>
> 13. 1. b. Bush Fires Act 1949 No. 31

Fuel reduction burning is one of the most commonly employed methods to manage areas prone to develop bushfires (Luke and McArthur, 1978). Clearing strips of vegetation to act as fire breaks and establishment of fire trails are additional strategies employed to control bushfires and are required by law (Bush Fires Act, Section 13. 1. a).

The changes in fire regime described above and additional fire suppression techniques have raised concern about possible detrimental impacts on the Australian environment (Greene *et al.*, 1990; Atkinson, 1984; Good, 1981). The main issues under consideration are:

i. the degradation of ecological integrity and loss of biodiversity (Fox and Fox, 1986; Good, 1981) and,
ii. the degradation of soil and water quality by increased runoff and erosion (Good, 1996; Greene *et al.*, 1990; Atkinson, 1984; Good, 1973).

2.3 Types of Fire, Roles and Impacts

Luke and McArthur (1978) point out that the occurrence of fire in the landscape requires the coincidence of flammable fuel and a source of ignition. In this review, these authors describe factors controlling the spread and intensity of fire. These factors include the type, amount and continuity of fuel. Fuels may consist of living vegetation or accumulated dead plant material including wood, leaf litter, seed capsules and straw.

Luke and McArthur (1978) state that climatic factors are also important. The antecedent moisture content of fuel must be low enough to enable ignition and combustion to occur. Under natural conditions, prolonged dry spells and high temperatures during summer and autumn may provide these conditions. The weather conditions during a fire also have an effect on intensity and spread of the burn. Hot, dry and gusty conditions can result in rapid spreading of fire and the formation of broad and intense burning fronts. This type of fire is commonly described as wildfire.

2.3.1 Fires of High Intensity - Wildfire

Natural wildfires; ie. those fires which are not a result of direct or indirect human intervention, are infrequent events today because of the extent of landscape change following settlement. This is because the coincidence of all the variables required for a burn to ignite and develop into a wildfire is relatively rare (Luke and McArthur, 1978).

As mentioned above (Section 2.1.4), Gill (1981a) and Singh *et al.*, (1981) described how humans have changed the natural fire regime by modifying the landscape and providing new sources of ignition. One of the most significant modifications to the landscape has been the alteration and fragmentation of natural vegetation cover (Gill, 1981a). Luke and McArthur (1978) also point out that humans have provided many more sources of ignition through the deliberate or unintentional use of fire and artefacts of technology be they discarded glass bottles or powerlines. Lightening strikes were probably the only or at least most common sources of ignition before human intervention (Singh *et al.*, 1981).

The intensity of fire is related to *available fuel* rather than the absolute amount of fuel (Luke and McArthur, 1978). Available fuel is the proportion of fuel which will actually combust during a fire. Flammability of fuel depends greatly on moisture content. Finer fuels such as leaf litter and twigs dry out or *cure* more quickly than large logs and tree stumps. At any one time, available fuel is therefore much more likely to consist predominantly of fine or *annual* fuel. As climatic conditions have a controlling effect on plant productivity, annual fuel is greatly affected by the characteristics of each growing season (Walker, 1981; Luke and McArthur, 1978). For example a wet winter and spring followed by a hot summer would be conducive to a large quantity of available fuel in the late summer-autumn period.

In contrast to annual fuel, large fuels such as logs would require prolonged dry spells to cure enough to burn readily and completely (Luke and McArthur, 1978). It takes much longer for logs to dry out because they have a small surface area to volume ratio. Only long spells without rain or high atmospheric moisture will result in cured, large fuels. This is because dead vegetation is *hygroscopic*, ie. plant cells retain their structure after death and therefore adsorb water vapour from the atmosphere (Luke and McArthur, 1978). Even then, do these larger fuels not affect the rate of spread and intensity of the fire-front (Cheney, 1981; Luke and McArthur, 1978). This is because the rate of combustion is also affected by surface area and availability of oxygen which becomes limiting for larger diameter fuel. These fuels would therefore burn as a result of the wildfire-front passing rather than contributing to its spread. As these large fuels burn slower but for longer, their effect on the underlying soil is potentially different in that of a fine-fuel-only fire passing over the soil which may be intense, but short-lived (Cheney, 1981).

2.3.2 Fires of Low to Moderate Intensity

The scenarios so far described have focussed on factor contributing to the propagation of fire in the landscape. As discussed, natural wildfires develop when ignition occurs under conditions which are favourable to a rapid spreading of the fire and burning of fuels resulting in a high intensity and often widespread burn. When the environment is less favourable, under natural conditions, ignition rarely occurs. This is because, as discussed, potential sources of ignition are rare and if there is little cured fuel present, the probability of coincidence between ignition source and flammable fuel is low (Luke and McArthur, 1978).

Sources of ignition resulting from anthropogenic activities are much more frequent than under natural conditions (Luke and McArthur, 1978). The occurrence of fire in environments less favourable to natural wildfires is therefore more likely. Fire under these conditions spreads less rapidly, burns less intensively and often results in only partial combustion of fuels (Cheney, 1981, Luke and McArthur, 1978). Such fires are sometimes referred to as *cool burns*. These characteristics mean that low intensity burns are easier to control and are thought of as being less destructive than wildfires due to the lower temperatures and because more soil cover remains after the burn (Prosser, 1990; Humphreys and Craig, 1981; Debano *et al.*, 1979; Wells, 1971). Also, because of the less intense heat during such a fire, damage to plants tends to be less and they can recover more quickly. Lower temperatures also avoid the loss of nutrients through volatilisation and can increase the short term fertility of the soil by returning ash to the soil surface as a nutrient rich mulch therefore stimulating recovery (Khanna and Raison, 1986; Walker *et al.*, 1986; Wells, 1971). Humans have therefore been using deliberately lit fires during cool, calm weather conditions and while fuels are relatively moist to reduce potential available fuel for wildfires. This type of fire is referred to as a *control burn* or *fuel reduction burn* (Luke and McArthur, 1978).

2.4 Effect of Fire on Soil Properties and Water Erosion

Sections 2.1 and 2.2 introduced some general concepts on the relationship of fire with vegetation and the soil-plant system. Section 2.3 examines some of the implications of these concepts to management and geomorphic processes which drive landscape evolution. In this section, literature on the effect of fire on soil properties and erosion are considered in more detail.

The effect of fire on soil properties and soil erosion needs to be considered on several levels and tends to be highly variable depending on location (Walker *et al.*, 1986; Clinnick, 1984; Humphreys and Craig, 1981; Debano *et al.*, 1979; Wells *et al.*, 1979; Debano *et al.*, 1977; Debano and Krammes, 1966). This is a result of the compounding effect of differences in the severity of heating over and above those already variable processes of soil pedogenesis and soil erosion.

Several studies (Humphreys and Craig, 1981; Debano *et al.*, 1979; Wells *et al.*, 1979; Debano *et al.*, 1977; Debano and Krammes, 1966) have showed that the intensity of a fire and a range of soil properties, such as texture and moisture content, control to what depth and temperature the soil is affected (Figure 2.3). These factors also control the combustion of organic matter, dormant seeds, cover and damage to living plants (De Ronde, 1990; May, 1990; Gill *et al*, 1981; Debano *et al.*, 1979; Wells *et al.*, 1979). The damage to plants and loss of seed store can affect post-fire recovery, which in turn affects soil exposure to erosive forces such as raindrop impact and overland flow (Clinnick, 1984; Debano *et al.*, 1979).

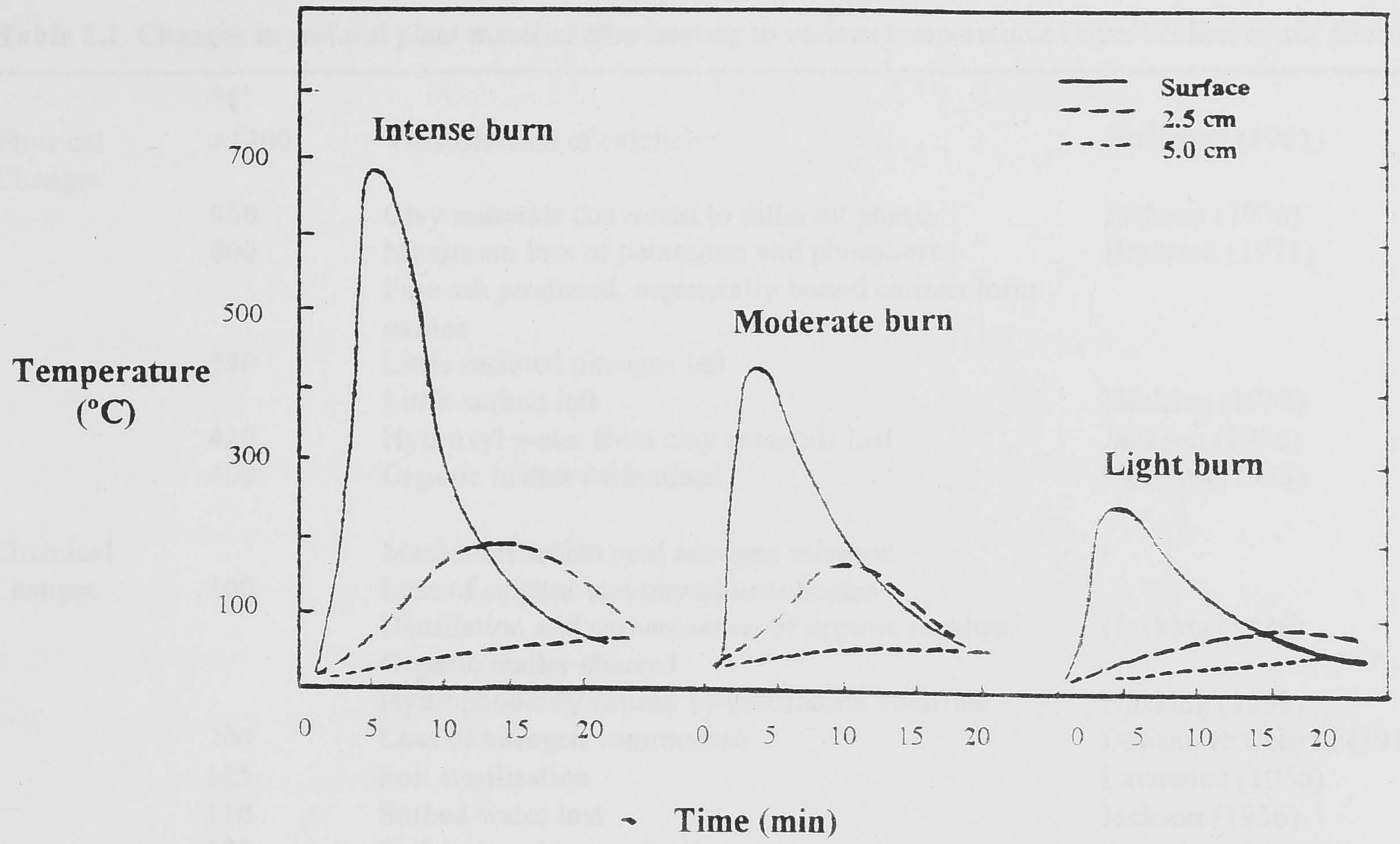


Figure 2.3: Soil temperatures at 0, 2.5 and 5 cm depth, after Debano, 1982.

Generally, the more intense the burn, the more severe and long-lasting are the effects on soil and soil erosion (Debano *et al.*, 1979). This is because a severe burn affects vegetation and soil to a greater extent via the heating process and because it results in more complete combustion of soil cover. Luke and McArthur (1978) and Cheney (1981) point out however that the fire-fronts of some intense wildfires move very quickly and the short residence time may reduce the impact on soil.

Fire can temporarily and sometimes permanently change soil properties such as erodibility and hydraulic characteristics (Valzano *et al.*, 1997; Humphreys and Craig, 1981; Debano *et al.*, 1979; Debano *et al.*, 1977). This is achieved by heating of the upper soil layer and the deposition of ash. Ash and other debris can clog pores reducing infiltration capacity. Volatilised organic matter can coat soil particles and aggregates, resulting in water repellence or *hydrophobicity*.

Compared to other forms of disturbance such as tillage or trafficking during logging operations, the modification of physical soil properties during the heating process is relatively minor. Prolonged exposure of the soil to very high temperatures (see Figure 2.3) can result in structural changes to soil (Table 2.1). These conditions are more likely to occur under windrow and slash burning than during wildfire (Walker *et al.*, 1986; Humphreys and Craig, 1981). The lower range of temperatures indicated (up to about 300° C) by Figure 2.3 and Table 2.1 are more representative of temperatures under natural fires (Walker *et al.*, 1986; Humphreys and Craig, 1981; Debano *et al.*, 1979) which mainly affect chemical and biological properties of soils.

Table 2.1. Changes in soil and plant material after heating to various temperatures (after Walker *et al.*, 1968).

	°C		
Physical Changes	>1200	Volatilisation of calcium	Hodgman (1962)
	950	Clay minerals converted to different phase	Jackson (1956)
	600	Maximum loss of potassium and phosphorus	Braswell (1971)
		Fine ash produced, organically bound cations form oxides	
	540	Little residual nitrogen left	
		Little carbon left	Hosking (1938)
	420	Hydroxyl water from clay minerals lost	Jackson (1956)
	400	Organic matter carbonised	Hosking (1938)
Chemical Changes		Maximum amino acid nitrogen released	
	300	Loss of sulphur and phosphorus begins	
		Distillation and carbonisation of organic residues	Hosking (1938)
		Organic matter charred	
		Hydrophobicity caused by distillation volatiles	Hosking (1938)
	200	Loss of nitrogen commences	Debano & Conrad (1978)
	125	Soil sterilisation	Lawrence (1956)
	110	Sorbed water lost	Jackson (1956)
	100	Soil ammonium production starts	Russel *et al.* (1974)
	70	High nitrate mineralisation	
	60	Proteins denatured	Dawson & Johnson (1965)
Changes to Biological Activity	50	Mild sterilisation owing to water loss	
	37	Maximum stimulation of soil micro-organisms	Funke and Harris (1968)
	<25	Usual soil temperatures	

2.4.1 Aggregation and Erodibility

Field and laboratory studies have shown that very high temperatures (in excess of 600° C) are required to alter mineralogy and thus permanently affect soil structural properties such as soil strength and structure (refer also to Section 2.3, Table 2.1).

The destruction of organic matter, which begins at approximately 200° C and is very rapid at 400° C (Humphreys and Craig, 1981), can have negative effects on soil structure and aggregation (Giovannini and Lucchesi, 1983; Giovannini *et al.*, 1983; Giovannini *et al.*, 1990; Debano *et al.*, 1977). The role of organic matter in improving soil structure, aggregation and water holding capacity is well known (Haynes and Swift, 1990). Loss of this organic matter leads to and increase in bulk density and loss of porosity which restricts the movement of air and water through the soil (Imeson *et al.*, 1992; Murphy, 1990; Hillel, 1980).

Several studies have shown that heat can have an aggregating effect on the fine mineral fraction which becomes permanent at temperatures above 400° C (Giovannini and Lucchesi, 1983; Giovannini *et al.*, 1990; Humphreys and Craig, 1981). While this can be beneficial in improving the structure of undesirably heavy soils (Sreenivasan and Aurangabadkar, 1940), in well structured or coarse textured soil the detrimental effects of heating tends to be greater than any beneficial effect detected (Greene *et al.*, 1990; Giovannini and Lucchesi, 1983; Humphreys and Craig, 1981; Debano *et al.*, 1979).

Few studies have attempted to isolate the effects of fire on soil erodibility rather than study the combined effect of fire on erodibility and erosivity due to loss of soil cover (Section 2.4.1) and increases in runoff (Section 2.4.2). Greene *et al.*, (1990) measured decreased macro-aggregation and increased micro-aggregation in the upper 1.0 cm of soil. Ueckert *et al.*, (1978) showed a similar trend with a percentage decrease in the >2.0 mm water-stable-aggregate fraction while the <0.25 mm fraction increased. Giovannini and Lucchesi (1983) found that the topsoil decreased in organic matter content and aggregate stability, while the underlying B horizons showed an accumulation of organic and hydrophobic substances which resulted in increased aggregated stability.

2.4.2 Infiltration

The loss of surface cover through burning results in an exposed soil surface prone to degradation by forces of erosion including raindrop impact and overland flow. Impacting raindrops not only detach soil but also apply compressive energy to the soil surface (Bradford and Huang, 1992; Bradford *et al.*, 1986; McIntyre, 1958). This compaction; combined with clogging of soil pores by small particles that are detached by the impacting drops, can result in surface sealing which results in a reduction in infiltration capacity (Giménez *et al.*, 1992; Le Bissonnais and Singer, 1992; Tanaka *et al.*, 1992). This phenomenon is commonly observed in cropped agricultural land where it is cause of much concern (Hudson, 1986), but also occurs in soils affected by fire (Debano *et al.*, 1979).

Ash fragments littering the surface as by products of the combustion process have been observed to have a similar effect as detached soil particles have in the sealing process (Debano *et al.*, 1979). The role of clogging of pores by ash following fire has received some speculation (Debano *et al.*, 1979) but no conclusive studies have shown that it actually has a significant impact. Valzano *et al.* (1996), showed significant reductions in infiltration rates following stubble burning. As the experiments were carried out using a disc permeameter, surface sealing by compaction can be discounted as being the cause of the reduction in infiltration. Also, tests for water repellence indicated that this process was also not contributing to the reduction in soil hydraulic properties. Micromorphological investigation of the surface seal were however inconclusive.

The effect of water repellence on infiltration has received much attention (Dekker and Ritsema, 1994; Scott and Van Wyk, 1992; Crockford *et al.*, 1991; Burch *et al.*, 1989; Debano *et al.*, 1979; Debano *et al.*, 1977; Debano and Letey, 1968; Debano and Krammes, 1966). Water repellence is a phenomenon whereby soil resists the uptake of water. The cause of this resistance is an increase in the solid-liquid contact angle due to the coating of soil aggregates by hydrophobic substances (Ma'shum *et al.*, 1988; Ma'shum and Farmer, 1985; Debano *et al.*, 1979; Bond, 1968; Debano and Letey, 1968; Bond, 1964). Coarse textured soils are much more prone to becoming water repellent than fine textured soil. This is because coarse textured soils have a smaller surface area and are therefore more effectively coated by these substances (Giovannini and Lucchesi, (1983). Nevertheless, water repellence has been observed in some finer textured soils (McGhie and Posner, 1980).

The occurrence of water repellence in soil is not uncommon and may be more widespread than is commonly believed (Bond, 1968). The mechanisms by which water repellence is induced in a soil may include leaching of organic compounds from litter, growth and secretions by fungal hyphae and burning (Savage, 1975; Savage, 1974; Savage, 1968).

The process by which burning induces water repellence involves the volatilisation of organic compounds in the combustion process, the movement of the organic compounds as a vapour into the soil profile and the condensation of vapour on cooling (Figure 2.4).

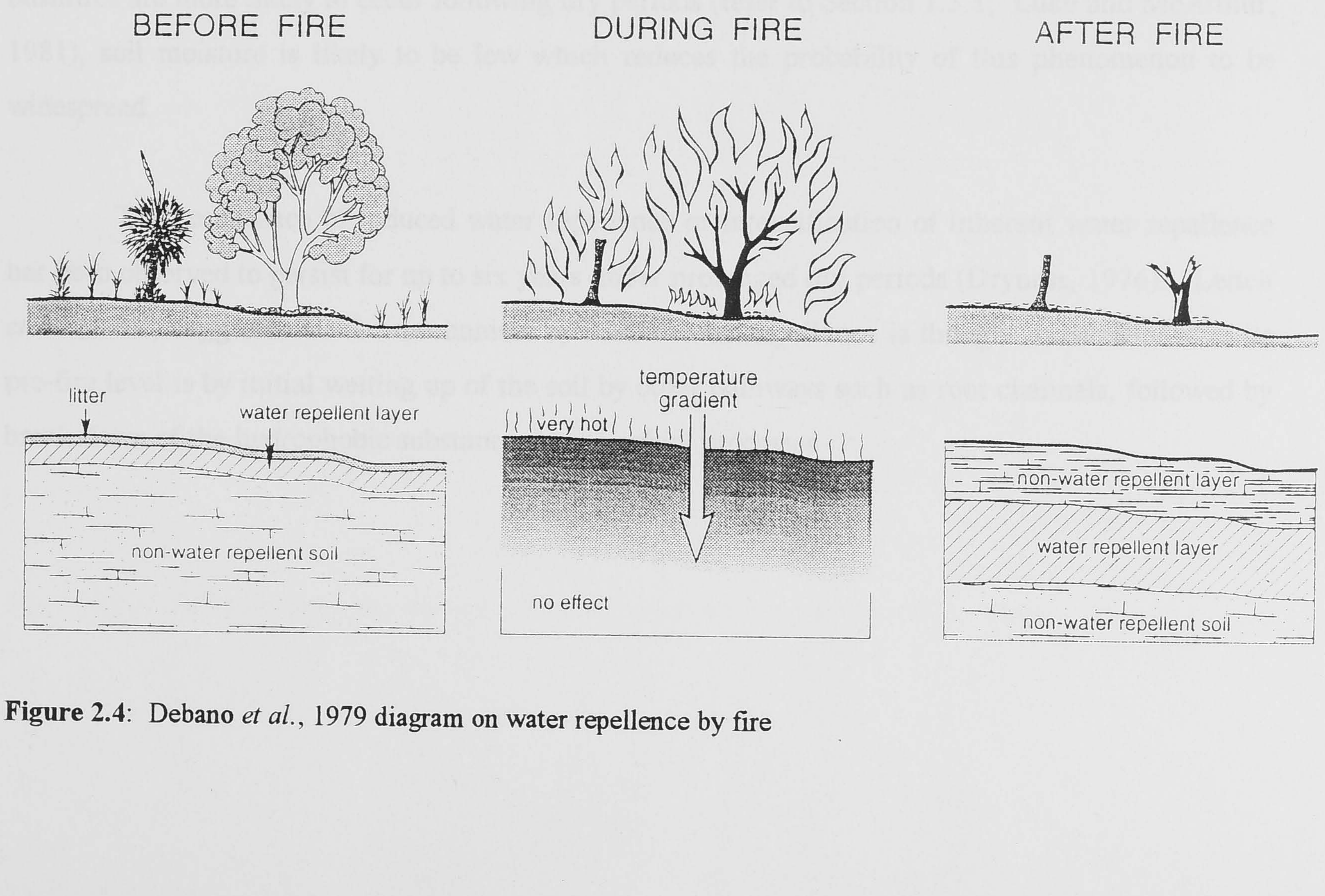


Figure 2.4: Debano *et al.*, 1979 diagram on water repellence by fire

If water repellence was present in the soil before a fire, the fire may simply result in the relocation of the water repellent layer as shown in Figure 2.4. The distribution of the water repellent layer following fire depends on the temperature gradient through the soil profile (Debano *et al.*, 1976; Debano and Krammes, 1966; Krammes and Debano, 1965). The temperature at the surface of the soil may be so great that it volatilises previous organic coatings or prevents the condensation of other compounds in the top few centimetres of soil. In this instance, the water repellent layer will tend to occur lower down in the soil profile.

Several studies have shown that the antecedent soil moisture has a great influence over the severity of water repellence (Dekker and Ritsema, 1994; Debano *et al.*, 1979; Debano, 1971; Gilmour, 1968; Gilmour, 1967). Field observations and laboratory experiments by these and other authors have shown hydrophobic soils of low moisture content are more repellent. These studies also demonstrated that thoroughly wetted hydrophobic soil conducts water at the same rate as an equivalent non-hydrophobic soil. Because of the importance of soil water content, the effect of fire on soil water repellence can therefore be twofold: 1. translocation of hydrophobic substances onto soil (Debano *et al.*, 1976, Savage, 1974) and 2. drying out of the soil and activating inherent soil water repellence (Debano *et al.*, 1979).

Soil moisture at time of the fire has also been shown to be important as it affects the temperatures reached by the soil (Debano *et al.*, 1979). For soil to reach high temperatures, the soil must be dry first. Scotter, 1970 showed that when there is water present in the soil, the temperature of the soil does not exceed 100° C until the water has been evaporated. Dryness (1976) found that a higher soil moisture content at the time of burning resulted in more severe water repellence. Since bushfires are more likely to occur following dry periods (refer to Section 1.3.1; Luke and McArthur, 1981), soil moisture is likely to be low which reduces the probability of this phenomenon to be widespread.

The persistence of induced water repellence or intensification of inherent water repellence has been observed to persist for up to six years under prolonged dry periods (Dryness, 1976). Leitch *et al.* (1983) suggests that the mechanism by which water repellence is thought to be reduced to its pre-fire level is by initial wetting up of the soil by other pathways such as root channels, followed by break down of the hydrophobic substances by microbial processes.

2.4.3 Soil Cover

The reduction or complete removal of living vegetation and other combustible soil cover can have a significant effect soil water balance, soil erosion and runoff generation (Hudson, 1986; Lang and McCaffrey, 1984; Lang, 1979; Morgan, 1979; Meyer and Mannering, 1971).

Fire can kill or damage living plants which reduces evapotranspiration and affects the water balance within the soil water system (Rambal, 1994; Kuczera, 1985; O'Loughlin *et al.*, 1982). The loss of mulch cover can increase soil water evaporation. Regenerating plants after fire may use more or less water than a mature or senescent stand of vegetation. An example of this effect has been observed following wildfires in Mountain Ash (*Eucalyptus regnans*) forests by Kuczera (1985), who reported that catchment water yield increased over the background level immediately following burning and then decreased substantially during the regrowth phase.

Loss of plants and other forms of soil cover also exposes the soil surface to degradation by erosive forces such as raindrop impact and flow. The role of soil cover in protecting the soil from erosion and other types of degradation such as surface sealing is well documented (Figure 2.5, Moss, 1989; Hudson, 1986; Lang and McCaffrey, 1984; Morgan, 1979; Meyer and Mannering, 1971).

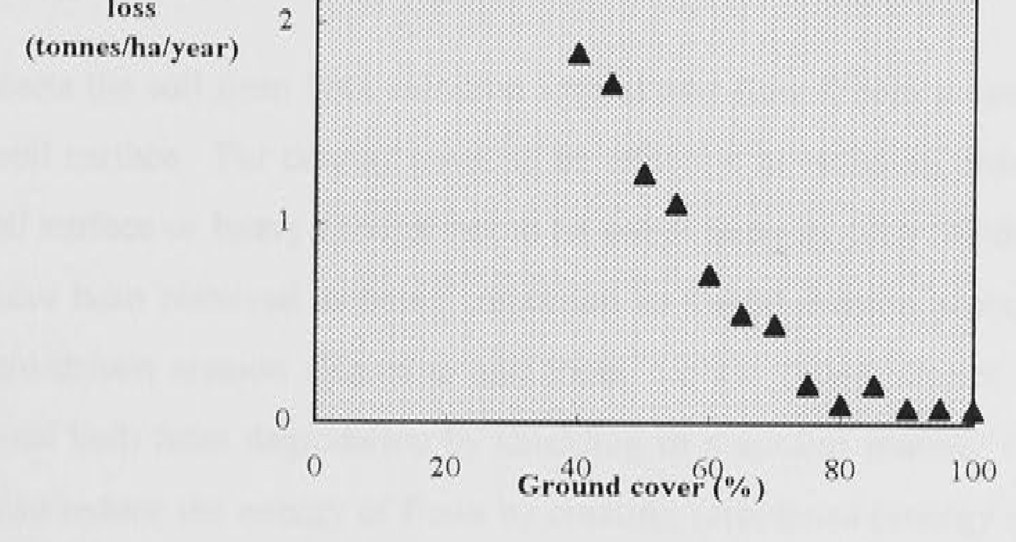


Figure 2.5. Relationship between soil cover and erosion (after Lang and McCaffrey, 1984).

Cover is generally classified as *contact cover* or *projected cover* according to its role in the erosion process.

Projected cover consists of plant canopy, leaf litter and similar materials which shield the surface from raindrop impact and therefore from rain-driven erosion processes (Moss, 1989). This type of cover may be close to the soil surface (grasses, mulches) or consist of several storeys depending on vegetation type (Daly and Hodgkinson, 1996; Fox and Fox, 1986; di Castri and Mooney, 1973).

The structure of the vegetation (or other) cover can significantly affect its influence on erosion processes. Crockford and Richardson (1990i-iv) demonstrated the effect of different canopies on the partitioning of rainfall in *Eucalyptus* forests and *Pinus radiata* plantations. These studies illustrate the different pathways and storages which govern the rate of which rainwater reach the soil surface. Moss and Green (1987) demonstrated that large drops forming at the end of leaves on trees and falling to the surface can be more erosive than natural rain if the fall height is sufficiently high.

Mauchamp and Janeau (1993) showed the beneficial effects of rainwater funnelling by shrubs. In this process, the structure of the plant encourages intercepted rainwater to flow along its stems. The study showed that the resulting stemflow accounted for up to 45 per cent of rain and applied the water gently to the soil surface around the base of the plant. Clipping of the bushes resulted in a redistribution of the rain and a reduction in permeability due to surface sealing. Plants which perform this function are common in periodically dry and fire prone areas (Moreno and Oechel, 1994; di Castri and Mooney, 1973) and have been shown to play an important role in the re-wetting of the soil, particularly if water repellence is reducing infiltration (Booker *et al.*, 1993; Rath, 1993). Similarly, the preservation of macropores under the protection of canopy and litter cover can perform an equivalent role (Greene *et al.*, 1994; Imeson *et al.*, 1992; Leitch *et al.*, 1983).

Contact cover protects the soil from both raindrop impact and flow driven processes and is in direct contact with the soil surface. For contact cover to be effective in reducing erosion rate, it must be anchored to the soil surface or heavy enough not to be swept away by flow (Hudson, 1986). Mobile armouring layers have been observed as being important in fluvial erosion processes (Moss and Walker, 1978) and rain-driven erosion (Hairsine and Rose, 1991). These layers protect the surface of the soil (or channel bed) from degradation by shielding in a similar manner to projected cover. Armouring layers also reduce the energy of flows by creating turbulence (energy dissipation) and absorbing energy a part of detachment - transport - deposition -re-detachment - ... processes (Moss and Walker, 1978).

Well vegetated surfaces can provide significant resistance to erosion by flow. The flume experiments by Prosser and Slade (1994) showed that swampy meadow type vegetation provided protection against flows of more than 1 in 100 year recurrence probability (see also Section 2.2.3). Even in landscapes where vegetation is sparse, vegetative soil covers provided by cryptogamic crusts (mosses, lichens and liverworts) have been shown to provide significant levels of protection against erosion (Greene *et al.*, 1990).

Two studies have showed that under specific circumstances, contact cover can have a negative effect on soil infiltration and erosion. Gilmour (1967) found that accumulated litter under *Eucalyptus* and *Pinus* was responsible for water repellence while bare areas did not display the same level of hydrophobicity. Singer and Walker (1983) measured that soil loss was higher with straw mulch than for bare areas. The authors attributed this to the attenuation of surface water by cover which increased the depth and transport capacity of flow over that of rain splash alone.

In most reported cases, the loss of contact cover through burning results in a smoother surface which can result in more rapid overland flow (Lavee *et al.*, 1995). Locally this tends to increase soil loss (Lavee *et al.*, 1995; Scott and Van Wyk, 1992; Atkinson, 1984; Debano *et al.*, 1979) while on a global scale it can affect catchment hydrology (Scott and Van Wyk, 1992; Cornish and Binns, 1987; Good, 1973; Brown, 1972).

2.4.4 Effect of Fire on Runoff and Erosion

So far Section 2.4 has discussed the effects of fire on a number of soil properties and how each of these relates to erosion. In this section, observations on the combined effect of fire on soil erosion processes are examined and related to other erosive environments.

The literature examined in Section 2.4.1 indicated that fire reduces aggregation and therefore increases the erodibility of topsoil. Fire also has a deleterious effect on infiltration (Section 2.4.2). Water repellence and surface sealing commonly observed after fire result in an reduction of infiltration of rain and increased runoff. Section 2.4.3 describes the role of cover in protecting the soil from erosion. A reduction of soil cover by burning leads also to an increase in erosion.

The combined effects of fire on the soil-plant system is to increase its vulnerability to erosion. The extent to which fire affects erodibility varies with fire intensity (Figures 2.3 and 2.4) and from one landscape system to another. The occurrence and severity of erosion by water is also dependant on the timing and characteristics of rainfall (Hudson, 1986).

Several authors have discussed the implications of coincidence of intense rainfall events with a fire affected landscape (Prosser and Williams, 1997; Booker *et al.*, 1993; Good, 1973), but few have reported such events (Atkinson, 1984; Leitch *et al.*, 1983; USDA, 1954).

Even under *normal* climatic conditions, erosion rates following fire are expected to increase when compared to the pre fire level, due to the lowering of resistance discussed above. While the scale of this increase depends on climatic conditions experienced after a fire and the extent of impact by the fire, it is useful to compare potential impacts of fire with those caused by other disturbances.

In most other forms of disturbance of a landscape where vegetation cover is removed or altered other than by fire alone, there is additional soil disturbance associated with the soil cover removal process (Auzet *et al.*, 1995; Lacey, 1993; Hudson, 1986; Roberts and Church, 1986; Burgess *et al.*, 1981; Rice and Datzman, 1981). These disturbances include agricultural harvesting, logging operations, land clearing for plantations or other uses, road construction and urban development. Greene *et al.*, (1994a,b) have shown that under a grazing regime, trampling by stock can also lead to significant disturbance of the soil surface.

This additional disturbance can result in mechanical breakdown of soil aggregates and deterioration of soil structure. This is a common problem in agricultural soils where tillage is used to control weeds and prepare the soil for crop planting (Hudson, 1986). The disturbance of the soil surface and breaking up of soil aggregates increases the erodibility of the soil and its susceptibility to surface sealing (Hudson, 1986). Non-coherent or dis-aggregated soil is highly erodible by wind or water (Hudson, 1986).

In fire affected landscapes, the erosion observed on burned but otherwise undisturbed areas is generally less than that occurring on areas that were disturbed and burned such as cleared fire breaks, tracks and trails (Booker *et al.*, 1993; Atkinson, 1984; Good, 1973). This indicates that the increase in erosion due to fire alone is less than that resulting from additional disturbances in a post-fire environment.

2.4.5 Effect of Fire on Catchment Hydrology and Sediment Yield

Section 2.4.5 discusses how the combined effects of soil surface sealing and water repellence reduces infiltration capacity of the soil, while the loss of cover reduces interception and canopy storage of water. These effects have been shown to increase the volume and rate of runoff (Debano *et al.*, 1979). Reduced roughness of the soil surface also leads to increased flow velocity on slopes and a reduced time of concentration (Lavee *et al.*, 1995).

On a catchment scale, these changes in soil water hydrology and surface characteristics can result in increases in water yield and discharge characteristics. Drainage lines and other areas where flows merge are therefore likely to be stressed by erosion and sedimentation (Booker *et al.*, 1993; Good, 1973).

Following large wildfires the effect of burning may be very widespread and severe. Good (1973) reported the effects of widespread burning and remarked on the severity of erosion in specific areas, particularly on tracks and trails. Mackay and Robinson (1987), Burgess *et al.* (1981) and Brown (1972) all reported significant responses in catchment hydrology following large wildfires in Australia. Similar responses have also been observed overseas (Scott, 1993; Scott and Van Wyk, 1990; Campbell *et al.*, 1977). Leitch *et al.*, (1983) reported the burning of large areas following the Ash Wednesday bushfires in the Central Victorian Highlands. These authors reported catastrophic erosion responses following rain due to the severity and completeness of the fires.

Catastrophic responses to rainfall events in fire affected catchments have been reported by other researchers also (USDA, 1954). While these are generally attributed to the increase in peak discharge and quick-flows (Wells *et al.*, 1979), landscape geomorphology appears to have a significant influence. In the fire-flood sequence observed in southern California, colluvial valley deposits are mobilised by increased levels of runoff following fire (USDA, 1954; Booker *et al.*, 1993). The colluvial valley infills accumulate between fires due to dry ravel erosion, a gravity driven process in mountain ranges that are tectonically active and where soils are mostly non-cohesive gravels and sands. Fire triggers an erosion response in the form of mud and debris flows which represents a flushing of the drainage network.

Scott (1993) points that the connectivity of the drainage system has a large bearing on the response observed at the point of discharge from a given catchment. Scott (1993) observed that roads, tracks and skidpaths within managed forests can become extensions of the drainage system and enhance the efficiency of runoff routing and sediment transport to streams. He observed that this further accentuated the effects of wildfire on hydrological response.

Discontinuity in the surface drainage network as may be achieved by incomplete burning or by topography can greatly reduce the impact of sedimentation on the downstream resource. Imeson *et al.* (1992) observed that areas where soil cover and infiltration capacity remain high due to incomplete burning acted as buffers or filter zones following a fire in the Catalonia region of Spain. They described the vegetation pattern following a patchy burn as a mosaic with runoff and sediment producing areas where the fire had been more intense and run-on areas which had not been severely affected and could infiltrate the additional water. Scott and Van Wyk (1992) observed a similar pattern. They used a comparison of runoff plot studies and catchment monitoring following fire in a South African mountain Fynbos catchment. The plot studies indicated significant effects of fire on the soil which resulted in elevated rates of runoff and erosion. At a catchment scale however, no significant differences could be detected. The researchers remarked that the burn had been moderate and that different results would be expected for a more severe wildfire.

2.5 Rates of Erosion following Fire

A wide range of hydrological and erosion responses to fire has been recorded (Scott and van Wyk, 1992). Table 2.2 summarises observations and experimental results from the literature. As each study is different, the key variables identified by the authors have been listed for each study. Some of the data was sourced from previous reviews. In these cases, the comments provided are those provided by the authors of the review.

The data summarised in Table 2.2 comprises a wide range of landscapes, fire intensities and post-fire climatic conditions. This is reflected in the variability of hydrological and erosion response presented. The overall spread of data ranges from zero or negligible impacts (Versfeld, 1981; Biswell and Schults, 1976; Gilmour and Cheney, 1968) to erosion rates of 204 t $ha^{-1}yr^{-1}$ (Glendening *et al.*, 1961), 110 000 t day^{-1} (Brown, 1972), 116 000 t day^{-1} (Good, 1973) and 306 tha^{-1} for a single event (Colman, 1951). Where data on erosion from pre-fire erosion rates was available, percentage increase in sediment yield and runoff could be calculated. The percentage increase ranged from zero where there was no impact to 1 800 000 (Adams *et al.*, 1947) and 462 000 (Scott, 1993).

The data represent estimates of erosion rates measured on plot experiments and at a catchment level. The scale of measurement and baseline comparison needs to be considered when assessing the data for absolute value and trend. For example, the majority of landscapes represented are remnant forests (dry sclerophyll, wet sclerophyll, coniferous and hardwood), woodlands and shrublands that have been affected only by limited development and land use. Consequently, background erosion rates can be quite low, being in the order of 0.013 to 1.4 $tha^{-1}yr^{-1}$ (Scott, 1993; Smith and Stamey, 1965; Adams *et al.*, 1946). Any acceleration of erosion will therefore tend to result in a large percentage increase in erosion rate over the baseline measurement (eg. Lavee *et al.*, 1995: 0.10 to 0.32 gives 320% increase).

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
Sydney, Australia	Plot 9 m^2, slope 6-13 %	2 events of 1 in 10 year return period	dry sclerophyll forest on sandstone	uncontrolled wildfire		1st rain (low intensity): 0.17-0.4 tha^{-1} 1st 1in10 year event: 2.2-7.5 tha^{-1} 2nd 1in10 year event: 30-48 tha^{-1}		rates in 0-12 months, 0.17-0.4 $tha^{-1}yr^{-1}$ quoted as background erosion	Atkinson, (1984)
Southwest United States								Review of several papers	Baker, (1988)
Arizona			Chaparral,	Wildfire		204	117 000%	Glendening *et al.*, (1961)	
Texas	slopes: 1: 45-53% 2: 15-20%		Oak-juniper, Ashe-juniper	Control burn, dozing		1: 13.2-17.7 tha^{-1} 2: 0.43-2.4 tha^{-1}	140 000%	Wright *et al.*, (1976)	
California			*Pinus*	Understorey burn		nil erosion		Biswell & Schults (1976)	
California			Chaparral	Wildfire		55.3	1000%	Krammes, (1960)	
Sydney, Australia	Plot 8 m^2, slope 12°	ann. av. ppt: 1216 mm	Dry sclerophyll forest on sandstone		rain: 675mm in 1st year, runoff: 3-5%	2.5-8 (believed to be low due to drought period following the fire)		0-12 months	Blong *et al.*, (1982
Oakland, San Francisco			Sth Cal. - chaparral Oakland - various	Wildfire		Background erosion rates: Southern Cal.: 1.4 - 2.3 $mmyr^{-1}$ Oakland: 0.08 $mmyr^{-1}$		Comparison: Oakland vs and Southern California	Booker *et al.*, (1993)

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
SE NSW, Australia	Catchments 1: 87.5 $miles^2$ 2: 16.8 $miles^2$	Highest recorded: 27 $mmday^{-1}$	Wet sclerophyll forest, metasediments	Wildfire	Peak discharge 1: 116 ft^3s^{-1} 2: 334 ft^3s^{-1}	Sediment conc. (ppm): 1: 112 000 2: 143 000 sediment yield ($tday^{-1}$): 1: 45 100 2: 110 000	Peak discharge 1: 53% 2: 2110% sediment conc. 1: 33 500% 2: 2030% sediment yield 1: 25 000% 2: 41000%		Brown, 1972
SE NSW, Australia	Catchments relief 200m, slopes 10°-20° 95ha, 147ha		Sclerophyll forest on granite			*values given not referenced adequately but indicate up to 200% increase in sediment concentration*		some logging, erosion on roads observed, suggests that fire caused higher erosion than logging because of greater extend of impact	Burgess *et al.*, (1980)
Los Padres, California	Plots 3 x 12 m Slopes: 1: 20% 2: 60%		Mature chaparral on gravelly loams	Mod. to intense control burn		1: 2.8 2: 7.34	2: 3480%	Review of papers, data from erosion plots Debano and Conrad, (1976)	Debano *et al.*, (1979)
Galicia, NW Spain	Plots 80 m^2, slope 30%		Shrubland on granite	Control burn experiments	20%	0.27	Sediment: 144% Runoff: 120-125%		Diaz-Fierros *et al.*, (1990)

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
SE Arizona, USA	Evaluation areas (625 m^2) and runoff plots (32.5 m^2) slope 5-7%	av. ann. ppt: 400 mm	Rangelands dominated by lovegrass (*Eragrostis* sp.) and native grasses	Prescribed burns, 2 burns I year apart		0.029-0.292	142-180%		Emmerich an Cox, (1994)
Snowy Mountains NSW, Australia	Catchments 1: 142 km^2 2: 401 km^2 3: 43.5 km^2	Some high intensities observed: 60mmh^{-1} 2 days: 1: 155 mm, then 2: 86 mm	Montane to sub-alpine grass-, shrub- and woodlands, some forests	Severe wildfire	Maximum discharges recorded (cusecs) 1: 1010 2: 2350 3: 334	Sediment conc.(ppm) 1: 54 2: - 3: 143 000 sediment yield (tday^{-1}) 1: 141 2: 1031 3: 116 000	Values with vegetation cover: G: 14 ppm for 1000 cusecs, S: 631 & 415 tday^{-1} @ 2000 cusecs, W: no values given	Severe erosion on tracks and entrenchment of flow lines observed	Good, (1973)
Central Arizona, USA	Small catchments (0.01-0.2 ha)	annual average rain: 677 mm	Chaparral on granite	Wildfire		no buffer strip: 2.75	with buffer strip: 1.71%	*Comparison of micro-catchments sediment yields with and without riparian buffer strips, rates are 3 year averages from several plots*	Heede, (1988)

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
Gerona, NE Spain	Plots $100m^2$, slope not given but described as uniform	Simulated rain experiments 20-70mmh^{-1} av. ann. ppt: 700-800mm	Mediterranean type oak forest on acid igneous and metamorphic geology	Forest fire	*infiltration rates on burned plots are estimated at 50 to 70 % lower than unburned*		observed decrease of porosity in burned soil by 25%	*describe in detail the fire induced variability due to a patchy hydrophobic layer.*	Imeson *et al.*, (1992)
Mt. Carmel, Israel	Plots $1m^2$, slopes 8.5° - 12.5°	Simulated rain 30 mmh^{-1} for 2 hours (60 mm total ppt)	Mediterranean type shrublands and forests on limestone soils	Treatment unburned 0 weeks 2 weeks 52 weeks	 u: 14 0: 20 2: 32 52: 88	 u: 0.10 0: 0.32 2: 0.42 52: 0.36	 0: 320% 2: 420% 52: 360%	median values given for range provided by authors	Lavee *et al.*, (1995)
Central Highlands Victoria, Australia	Catchment 35 ha, slopes 20° - 28°	1 high intensity event: 30 mmday^{-1}	Sclerophyll forest on metasediments, gravelly and stoney soils	Intense wildfire	Discharge 0.5-1.0 cumecs	22 tha^{-1}	discharge: 1100%	observed mud and debris flows after large rain event, widespread water repellence	Leitch *et al.*, (1983)
SENSW, Australia	Plots 80-100 m^2 slopes 13° - 23°	av. ann. ppt: 450-500 mm	Sclerophyll forest and tussock grassland on metasediments	Mild to severe burns (grassfire on plots)	1% pre-fire 8% maximum observed in flowline	rate of surface lowering: 0.3-32 mm $10^{-3}yr^{-1}$,	1500 - 4500% on severely burned plot	*monitored natural rainfall and erosion and measured denudation rates before and after wildfire*	Prosser, (1990)

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
SW Cape, South Africa	Catchments 200 ha and 65 ha, mean slopes 26 and 46 % respectively	mean annual rainfall: 1300 and 1470mm	Fynbos associations on deep gravelly loams	High intensity wildfire	mean annual values: 45% and 36% increased after fire by 12.4%	erosion: 12-26 suspended sediment: 6 bedload: 1.8	*weekly flow rate increased by 12%* *quick flow volume increased by 201%* *peak flow rate increased by 290%*	*measured hydrological response to wildfire*	Scott and van Wyk (1990)
SW Cape, South Africa	Catchment 12 ha	mean annual rain (mm) 1275 m. ann. runoff (mm) 385	Mountain Fynbos on deep coarse loams	High intensity wildfire			Discharge: 133% peak flow: 400% (in 1st wet season)	Review of reported rates Ryecroft (1947); van Wyk (1987)	Scott and van Wyk (1992)
SW Cape, South Africa	Catchments 1: 324 2: 287	m. ann. rain 1: 1443 2: 1003 m. ann. ro 1: 694 2: 379	Mountain Fynbos on shallow to deep sandy loams, quartzitic sandstones	Prescribed burns at 6- and 12 year cycles		suspended sediment: 0.97×10^{-3} bedload: 6.5×10^{-3}	discharge: 15% (1st yr) sediment returned to normal after 10 months	van Wyk (1981), Lindley *et al.* (1988)	

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield (t ha^{-1} yr^{-1} unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
SW Cape, South Africa	Catchment 246	m. ann. rain 2261 m. ann. ro 1603	Overmature mountain Fynbos on deep gravelly loams	wildfire at end of wet season		suspended sediment: 0.148	yield normal by first wet season	van Wyk and Lesch (1989)	Scott and van Wyk (1992) cont'd
SW Cape, South Africa	Catchment 191	m. ann. rain 2300	Mature Fynbos on deep gravelly loams	Prescribed burn, moderate intensity		suspended sediment: 0.416 (3 year mean) bedload: 13.8 x 10^{-3} (3 year mean)	discharge: 16% (first 2 years) no change in stormflows	Scott and van Wyk (1992) - own results	
Southern Highland, Victoria, Australia	7 large catchments 1430 - 12800	m. ann. rain ca. 1450	*E. regnans* forest on deep clay loams	High intensity wildfire			reductions in flow by 24% for 21 years	Langford (1976)	
Montrose, California	Catchment	'severe rain event'	Mountain chaparral	Wildfire followed by severe rainstorm		estimation from single event: 306 tha^{-1}		Colman (1951)	
Yucaipa, California	Catchment 253	'severe rain event'	Mountain chaparral	Wildfire followed by high intensity rainstorm		estimation from single event: 25 tha^{-1}		Colman (1951)	

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield (t ha^{-1} yr^{-1} unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
Wheeler Springs, California	Catchment 10 625		Chaparral	Wildfire	no floods	little erosion observed		Colman (1951)	Scott and van Wyk (1992) cont'd
San Gabriel Mountains, California	Catchment, steep slopes		Chaparral	Fire			peak flow: 100-4400% dependant on storm size during 1st year	Rowe *et al.* (1954)	
Wilsons River, Oregon	Catchment		Temperate, coastal rain-forest	3 wildfires (1933-1945)		17 years after 1st fire: 3 tha^{-1}	discharge: 11% over 15 years peak flow: 45% immediately after fire, declining over 8 years sediment yield: 400-700%	Anderson (1976)	
Burns watershed, Washington State	catchment	m. ann. rain 579 m. ann. ro 112-175		Wildfire		massive debris, rock and soil flows observed	discharge: 120% for first 3 years	Helvey *et al.* (1976)	

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield (t ha^{-1} yr^{-1} unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
Rattle Burn, Arizona	Catchment 8.1	ca. 737, slopes <20%	Open pine forests on stoney soils	High intensity wildfire		1.7 39 tha^{-1} in first 6 months	sediment yield: 40 000% in first 2 years discharge: 700% in first year 280% in second year	Campbell *et al.* (1977)	Scott and van Wyk (1992) cont'd
Three Bar Watersheds Arizona	Catchment	m. ann. rain 620-750	Sparse deep-rooted chaparral on deep coarse soils	Wildfire			discharge: 900% in first year baseflows observed to increase also	Pase and Ingebo (1965)	
SW Cape, South Africa	Plot 0.08 ha Slope: 25%	m. ann. rain 1156	Fynbos and pine on deep sandy loams	Various including hoe and burn	Mean: 0.01-0.07% max. 0.65%	negligible		Versfeld (1981)	
SW Cape, South Africa	Plot 6 x 22 m Slope: 53%	m. ann. rain 2260	Overmature Fynbos on deep sandy loams	Wildfire	1.2-2.2%	0.4 (in first year)		Scott (1989)	
SW Cape, South Africa	Plot 6 x 22 m	m. ann. rain 2270	A: deep sandy loams B: deep gravelly loams	Prescribed burn	A: 3.1-4% B: 5.1-8.8%	A: 0.2-2.1 B: 1.9-7.3		Scott and van Wyk (1992) - own results	

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield ($t\ ha^{-1}\ yr^{-1}$ unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
Canberra, Australia	Plot 0.0006 ha Slope: 7%	simulated rain: 20mm @ 80 mmh^{-1}	*Pinus radiata* plantation	Prescribed fire		None	non-significant decrease in infiltration	Gilmour and Cheney (1968)	Scott and van Wyk (1992) cont'd
Wallaby Creek, NE Victoria, Australia	Plot 0.002 ha Slope: 36%	m.ann. rain 1220	Dry sclerophyll forest on stoney clay loams	Hot prescribed fuel reduction burns	2.5%	0.1-0.35	sediment yield: 100% recovery 1-5 years runoff: 100% recovery 3-5 years	Ronan (1986)	
North Fork, California	Plot 3 x 33 m Slope: 36%	m. ann. rain 840	Chaparral-woodland on deep sandy clay loam	1: undisturbed 2: twice burned 3: burned annually	1: 0.04% 2: 1.87% 3: 14.2%	1: 0.014 2: 9.1 3: 257	9 year averages - majority in first year, 2: 65 000% 3: 1 800 000%	Rowe (in prep.) cited in Adams *et al.* (1947)	
San Gabriel Mountains, California	various slopes: 55-95%		Unburned chaparral on non-cohesive soil	No treatment: baseline data		0.04-7.8, majority as dry ravel		Anderson *et al.* (1959)	
12 contrasting areas in USA	Plots 0.004 -2.2 ha slopes: 2-30%	m. ann. rain 500-1750	Humid sites suitable for agriculture	No treatment: plots under good cover	0.03-13.8%	0.22-1.4	considered to be natural erosion rates	Smith and Stamey (1965)	

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield (t ha^{-1} yr^{-1} unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
San Gabriel and Santa Ana Mountains, California	Plots 2 sites	m. ann. rain 1: 773 2: 949	Gravelly granitic loams	1: wildfire 2: wildfire	1: 9.7% 2: 9.9%	1: 346 2: 52		Krammes and Osborn (1969)	Scott and van Wyk (1992) cont'd
El Oso Creek, Arizona	various		Chaparral	Wildfire	3-90%	0.005-1.47		Heede *et al.* (1988)	
SW Cape, South Africa	Catchments 4	av. annual rainfall: 840-2270 mm	Fynbos associations	1 prescribed burn (low I) 3 wildfires		2.42 - 60 unburned: 0.013	erosion: 18600 - 462 000% peak discharge: 1110% quick flow: 92%	*measured hydrological response to wildfire*	Scott (1993)
NE California, USA	Plots 32.6m^2	av. annual rainfall: 335	Sagebrush community	Low intensity and high intensity prescribed burns		0-0.5 tha^{-1} depending on applied rainfall intensity	Low intensity: 100% High intensity: 510%		Simanton *et al.* (1988)

Table 2.2. Compilation of Erosion Response Reported in the Literature

Location	Plot or catchment size	Rainfall	Description	Treatment	Overland flow (as % of rainfall)	Sediment yield (t ha^{-1} yr^{-1} unless specified)	% increase over unburned (sediment yield unless specified)	Notes	Reference
	Mean annual rain (mm)		Burns of varying intensity					State-of-Knowledge Review	Wells *et al.*, (1979)
Mississippi	1620		Scrub Oak	Forest fire		0.132	130%	Meginnis, (1935)	
Oklahoma	777		Woodland	Burned annually		0.044	1100%	Daniel *et al.* (1943)	
N. Carolina	1190		Hardwood forest	Burned semi-annually		1.23	154 000%	Copley *et al.* (1944)	
Texas	1040		Woodland	Burned annually		0.144	720%	Pope *et al.*, (1946)	
Texas			*Pinus*	Single burn		0.084	210%	Ferguson, (1957)	
Mississippi	1650		Scrub oak	Burned and deadened		0.204	240%	Ursic, (1970)	
Boise Idaho			*Pinus*	logged and burned		0.15 m^3 ha^{-1}		Megahan and Molitor, (1975)	

Table 2.2. Compilation of Erosion Response Reported in the Literature

The scale of measurement is also important when assessing the data, for apparent discrepancies between plot and catchment scale may be indicative of processes that are not quantified by either mode of study. At the plot scale, immediate effects of fire on soil and cover are detected. The erosion rates measured by such experiments represent the actual increase of erosion at the hillslope level. As discussed in the previous section, the efficiency of the drainage network as a conduit for runoff and sediment will largely govern the response observed at the point of discharge for a catchment. This is reflected by studies such as Scott and van Wyk (1992) who measured sediment yield from plots (0.2-7.3 $tha^{-1}yr^{-1}$) and compared these with catchment sediment yields (0.42 $tha^{-1}yr^{-1}$).

The following Table (Table 2.3) is a summary of the compilation of recorded erosion response to fire and attempts to classify the observed trends using an arbitrary scale of not significant to catastrophic response.

Table 2.3. Summary of Trends in Erosion Response.

	Response (% increase in Sediment Yield)							
	not significant (0-10%)		**low to medium (10-500%)**		**medium to high (500-10 000%)**		**catastrophic (>10 000%)**	
Scale of study	**plot**	**catchment**	**plot**	**catchment**	**plot**	**catchment**	**plot**	**catchment**
Fire intensity	low intensity control burns	low or medium patchy burns	low to hot control burns	control burn, patchy,	moderate to intense control burns, wildfires	wildfire	annual burning	wildfires, complete burning of catchment
Rain or Runoff observed	low to medium	average	up to 70 mmh^{-1} simulated rainfall	average	high rain intensities	medium events	14.2% runoff - no intensity given	large rainfall events
Geomorphology/ Environment	slopes to 25%, woodland forests	various	woodland shrubland medium slopes	mountain Fynbos, medium slopes	medium to steep slopes, chaparral, forests	mountain Fynbos, medium slopes	hardwood forest, chaparral woodland	steep, mountainous terrain, forested/ chaparral
Type of Erosion	lack of runoff	lack of continuity	sheet erosion	sheet erosion,	sheet and rill erosion	sheet, rill and gully erosion		gully erosion, debris flows
Examples	Gilmour & Cheney, 1968; Versfeld, 1981	Biswell & Schults, 1976	Imeson *et al.*, 1992; Lavee *et al.*, 1995	Scott & van Wyk, 1992;	Atkinson, 1984; Debano *et al.*, 1979	Scott & van Wyk, 1990;	Adams *et al.*, 1947; Copley *et al.*, 1944	Good, 1973; Brown, 1972; USDA, 1958

This classification can be used to assess the variables which are associated with each magnitude of response. The table is also useful for interpreting some of the differences in response observed between catchment level studies and observations on erosion plots.

The *catastrophic response* column for example confirms that wildfire can lead to large scale responses when all the vegetation is burned, especially in steep catchments which can lead to quick accumulation and concentration of runoff especially under conditions of intense rainfall. By comparison, catastrophic erosion on a plot scale appears to be caused by very frequent burning which results in a bare and degraded surface for long periods of time. This difference can be explained as being a result of the type of burning regime. Frequent control burns generally do not affect the whole catchment as these fires tend to be patchy. In particular, moist riparian zones which can act as filter strips tend to remain intact. While individual slopes which are burned often may be degraded severely, the sediment does not leave the catchment and the increase in erosion rate therefore not detected at the catchment level.

At the other end of the scale, occasional mild burning may not elevate the *measured* rate of erosion above natural levels at all. This can be seen by the type of conditions characteristic of the *no significant effect* column. At a plot scale, fire may not have affected the soil surface sufficiently to decrease infiltration for runoff to occur, especially if favourable conditions prevail (ie. mild rainfall) in the post-fire recovery period. As described above, significant changes in runoff and erosion may not be detected above catchment base flows and background sediment yields due to discontinuity in runoff and sediment delivery to the point of discharge. Also, if there is no significant runoff and erosion on hillslopes, no increase in catchment scale erosion is expected.

There are a number of studies which do not fit readily into the proposed categories, ie. the prevailing conditions do not correspond to those for the majority of reports of the same level of response. This is likely to be a reflection of the attempted simplicity of the categories not catering for dominating effects. Also, as discussed earlier, many of the environments affected by burning have relatively low rates of background erosion which can result in high percentage increases even though the rate of post-fire erosion is not very high compared to other environments.

2.6 Background Erosion in the Sydney Area

The previous section described the general erosion and hydrologic response which have been reported for a number of ecosystems worldwide. The erosion rates described are useful for comparing post-fire conditions in a variety of landscapes and identifying geomorphological attributes which affect runoff and erosion processes triggered by fire.

This study has used a focus site in Royal National Park, near Sydney, which is described in the following Chapter. This section provides a summary of the rates of erosion provided by some studies in Australia, including some in the Sydney area in similar landscapes to ours, to give reference values for comparison and evaluation of the experimental results described in Chapters 5 and 6.

As mentioned above, there have been a number of studies in the area attempting to quantify soil erosion in the Sydney area. Humphreys (1985) summarised the recorded erosion response from some earlier studies in graphical form which is given below in Figure 2.6.

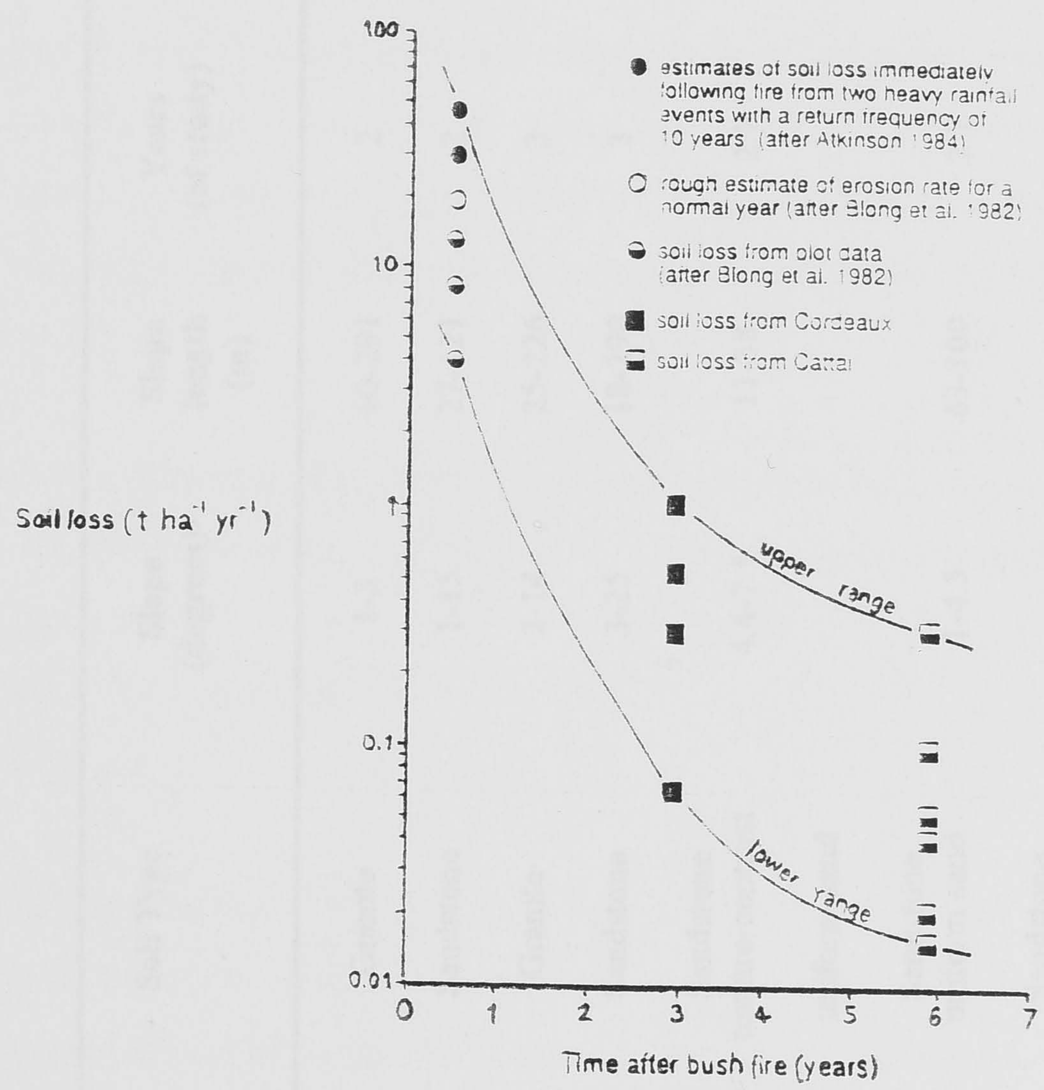


Figure 2.6. Reported soil losses after bushfires in the Sydney area (modified from Paton *et al.*, 1995).

As well as the bushfire studies, a number of other studies provide rates of soil loss which can be used for reference. While these rates do not give an adequate substitute for measurement of background erosion rate at the study site, the magnitude and range of erosion in similar areas can be used for general reference. Table 2.4 gives soil loss from granite and sandstone slopes (Williams, 1973) and from the Sydney Basin sandstone hillslopes (Humphreys and Mitchell, 1983).

Location	Soil Type	Slope (degrees)	Slope length (m)	Years (of study)	Average Annual Soil Loss ($tha^{-1}yr^{-1}$)	Range of Soil Loss ($tha^{-1}yr^{-1}$)
Northern Territory	Granite	1-3	60-291	2	0.76	0.17-2.37
Northern Territory	Sandstone	1-15	27-121	2	0.78	0.27-1.41
New South Wales	Granite	2-14	25-226	3	0.76	0.02-4.07
New South Wales	Sandstone	3-25	18-290	3	1.44	0.17-4.32
Cattai (Sydney)	Sandstone texture-contrast	4.4-7.5	11-38	2.7	0.04	0.02-0.08
	uniform sand				0.25	
Cordeaux (Sydney)	Sandstone uniform sand	1-4.5	63-100	2.7	0.32	0.04-0.68
Blackheath (Sydney)	Sandstone uniform sand	3-26	5-30	2.0	0.81	0.19-29.66
Lidsdale (Sydney)	Sandstone texture-contrast	0-10	5-180	2.9	0.86	0.07-6.97

Table 2.4. Background Soil Erosion Rates (after Humphreys and Mitchell, 1983; and Williams, 1973).

2.7 Conclusions

The processes of runoff and soil erosion are influenced by many complex and interrelated factors. Fire changes some of these factors, spatially and temporally. Fire affects soil cover, soil surface state, and biological, chemical and physical properties of the soil. Fire does not affect other factors which influence erosion such as soil texture or land slope. Also, while fire does not directly affect rainfall, the occurrence of fire is linked to climate, ie. hot and dry conditions, which means a link between rainfall and fire exists in that the post-fire conditions may follow certain weather patterns.

Assessment of the potential impact of fire requires evaluation of (i) the severity of the fire effects, (ii) the geomorphological attributes of the affected landscape, and (iii) the probability of erosive rainfall to occur.

(i) The severity of fire influences:

- the damage to vegetation which affects the length of the recovery process and survival of species, which in turn will affect long term stability of the ecosystem,
- loss of soil cover which exposes the soil to raindrop impact and overland flow, and
- heating of the soil which can change physical, chemical and biological properties of the soil.

(ii) The landscape attributes affecting runoff and erosion processes are:

- erodibility of the soil, ie. soil properties including hydraulic properties,
- topography,
- vegetation type, and
- land use.

(iii) Climatic factors include:

- erosivity of rain, gentle rain versus severe storm, and
- timing of rainfall for plants, ie. the regeneration of vegetation.

Many of these factors are related and isolation of individual relationships may be impossible and inappropriate. Nevertheless, in order to assess the overall effect of fire on soil and landscape processes, we must endeavour to understand relationships at all levels. This literature review has attempted to provide information relevant to the effect of runoff and soil erosion processes. This information may be used to interpret the results of this and further studies. The information is also useful in identifying the limitations of experimental studies and assisting to relate their results to other landscapes and conditions.

Chapter 3

Study Site

3. Study Site

3.1 General Background

The study site is located along the 'Big Marley Trail' within Royal National Park, approximately 50 km south of the Sydney, N.S.W, Australia (Figure 3.1). Royal National Park is the oldest national park in Australia, declared as such in 1879, and establishing Australia as the second country worldwide to dedicate land to this status. This status as well as Royal National Park's close proximity to the Sydney metropolitan area means that the area is both under pressure and scrutiny from large numbers of visitors each year.

Concerns about the degradation of this park as a result of human pressures (including the frequency of fires caused by arson) have been raised repeatedly. There are several studies in progress which are attempting to evaluate the impacts of these pressures on the ecology and biodiversity within the park. Even though there have been studies which have attempted to measure the effects of fire on soil erosion in the area (Prosser and Williams, 1997; Mitchell and Humphreys, 1987; Atkinson, 1984; Blong *et al.*, 1982) more detailed work is required.

The January 1994 fires in southern Australia affected substantial areas, mostly in New South Wales, but also in other states. The greater Sydney area was particularly impacted and more than 95 % of Royal National Park was burned. The fires in Royal National park and many other fires were deliberately lit by arsonists and burned out of control for several days. State-wide there was enormous damage to infrastructure, many injuries and 10 deaths occurred. The fires were consequently rated among the worst of this century and generated much publicity.

While the impact of fire on the loss of life and property received the main attention, concerns about the effects of the fires on the native vegetation and the potential for soil erosion to occur were also raised. The government agencies (the National Parks and Wildlife Service, the Dept. of Land and Water Conservation - then CaLM, Local Government groups and State Forests - then Forestry Commission of NSW) charged with managing the affected areas were consequently gathering information on what, if any, actions should be carried out to mitigate any degrading effects. A consultancy group, which had carried out broad-scale post-fire erosion treatments following the Oakland Fires (Booker *et al.*, 1993), publicly suggested that areas such as Royal National Park should be treated using techniques such as the broadcasting of ryegrass.

The fires had also generated interest in the scientific community who realised the opportunity presented by the fires to study ecological and geomorphological processes activated by the extensive burning of native bushlands. Also, the need for reliable data and information in general on the effects of fire in these landscapes and in Australia in general was realised when some of the above mentioned agencies met with representatives from research groups (the Commonwealth Scientific and Industrial Research Organisation, the Cooperative Research Centre for Catchment Hydrology and State Forest Research Division) to discuss proposed actions. It was as part of this initiative that the opportunity for this project was realised and funds provided to support it.

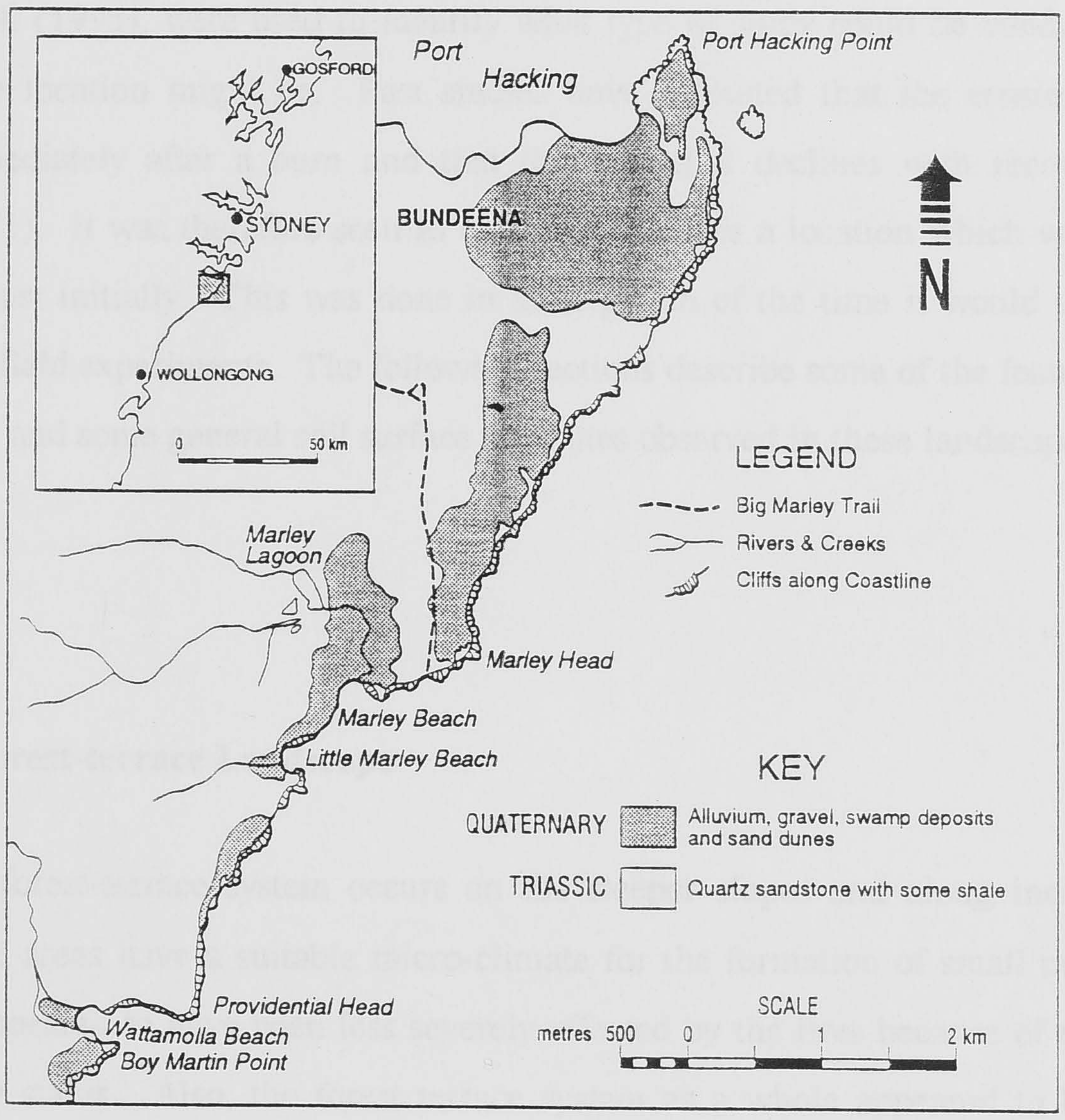


Figure 3.1. Map of the general study area (published in Zierholz *et al.*, 1995)

3.2 Early Field Observations and Selection of the Study Site

Royal national Park was chosen for both logistical reasons and because of the identified need for reliable data in an area that was of high conservation value, but under immense pressure from a variety of vectors. The study area chosen within the park was selected in collaboration with the National Parks and Wildlife Service who are the caretakers for National Parks and other reserves in the state of New South Wales.

Even though the environment represented by the site chosen for this study is of limited distribution, it is anticipated that the results will be applicable to other localities and therefore contribute to our overall knowledge of soil erosion processes activated by fire.

Also, although it would have been desirable to include a control area, ie. an equivalent, unburned site, no such areas could be located due to the extensiveness of the fires.

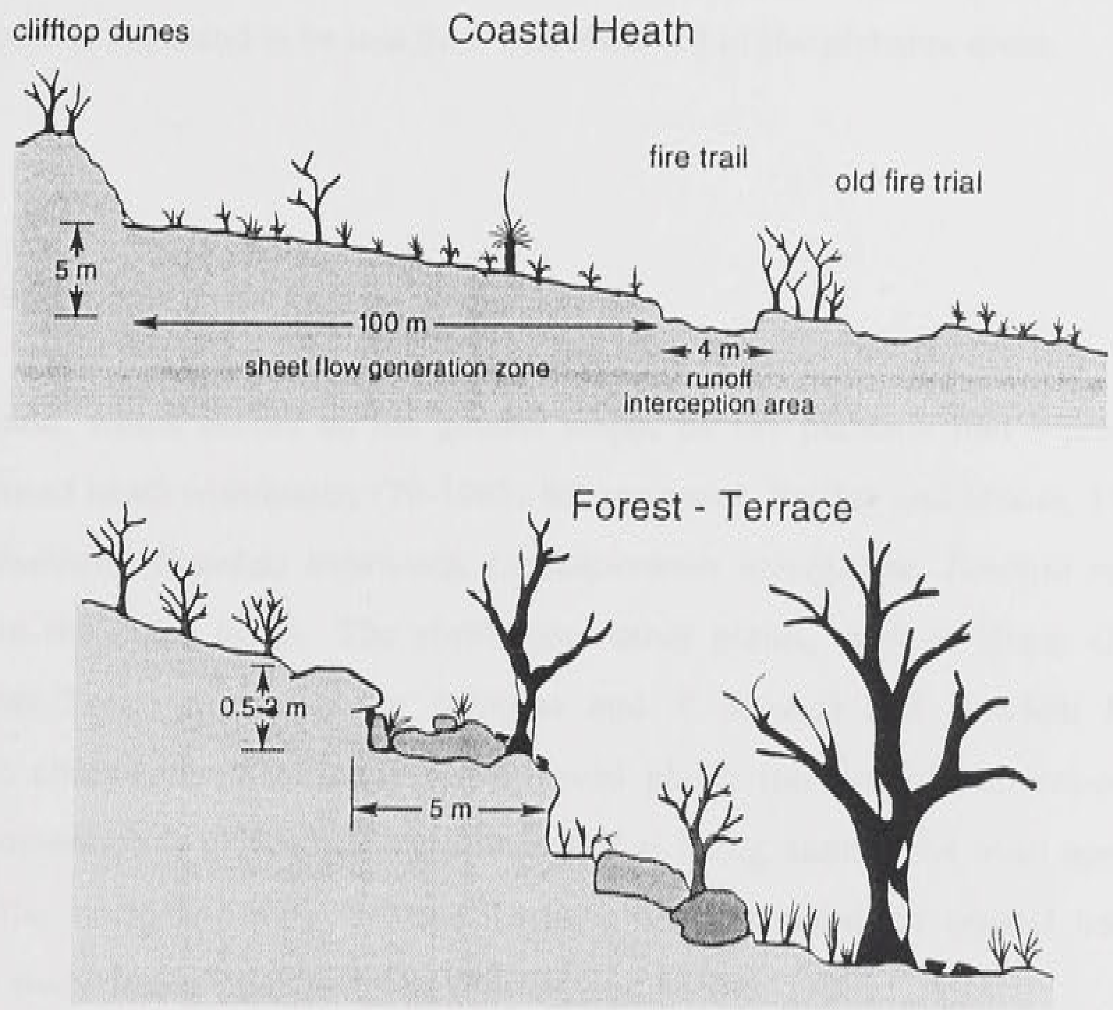
Observation of the area along Big Marley Trail indicated that there were two main types of landscape: (i) a forest terrace landscape and (ii) a coastal heathland. Both had been severely burned. These are depicted in schematically in Figure 3.2. Some early visits to the area, described in Zierholz et al. (1995), were used to identify what type of study could be conducted and where the most suitable location might be. Past studies have indicated that the erosion potential is at its greatest immediately after a burn and that this potential declines with recovery (Brunsden and Thornes, 1971). It was therefore seen as desirable to chose a location which was relatively slow to recover, at least initially. This was done in anticipation of the time it would take to organise and carry out the field experiments. The following sections describe some of the features of the two types of landscapes and some general soil surface attributes observed in these landscape as part of our field visits.

3.2.1 The Forest-terrace Landscape

The forest-terrace system occurs on the steeper slopes and along incised drainage lines. Some of these areas have a suitable micro-climate for the formation of small pockets of rainforest. These sites appeared to have been less severely affected by the fires because of their vegetation and high moisture status. Also, the forest terrace system as a whole appeared to be recovering more quickly, probably because of its relatively sheltered environment and vegetation.

Figure 3.3 shows the level of ground cover in this environment 8 weeks after the fires. Litterfall, bark and branch-shedding by the trees (*Eucalyptus* and *Angophora* sp.) contributed to relatively high levels of surface cover soon after the burn. Bracken fern (*Pteridium esculentum*) was also very quick to reshoot from its rhizome system and contributed significantly to soil cover in the first weeks after the fire.

The forest-terrace landscape is dominated topographically and hydrologically by the bedrock bench formations and rock outcrops. The rock outcrops provide surface roughness for routing of overland flow and the terraces act as impeding layers to water movement through the soil. Exfiltration of soil water at bench-steps was observed at many sites. The skeletal soils are confined to areas rock outcrops and gentler slopes on top of the benches. Much of this area was covered in ash and many seedlings were observed to be sprouting under the favourable conditions created by this layer.



Right:
Figure 3.2. Schematic diagram of the two main landscape types found in the north eastern part of Royal National Park (published in Zierholz *et al.*, 1995).

Below:
Figure 3.3.
Photograph of a typical site in the forest-terrace landscape showing the amount of rock outcrop and level of groundcover in early March 1994, approximately 8 weeks after the fires.

The apparent speed of recovery and logistical problems associated with the terrain for access and experimental design meant that this site was regarded as being less suitable for the purposes and scope of this study. Also, little erosion was observed in these areas and the threat of degradation resulting from runoff and erosion appeared to be less than that observed in the plateaux areas.

3.2.2 The Coastal Heathland

The coastal heathland, which occurs on the gentler slopes on the plateaux had a pre-fire vegetation consisting of a closed heath community (70-100% foliage cover, Fairley and Moore, 1989) dominated by *Westringia fruticosa*, *Baeckea imbricata*, *Leptospermum laevigatum*, *Banksia robur* and *Allocasuarina distyla* in the shrub layer. The shrubs and other plants, such as Blady Grass (*Imparata cylindrica*), Grass Trees (*Xanthorrhoea resinosa* and *X. media*) and Bracken Fern (*Pteridium esculentum*), are characterised by tough, hard-leaved plants tolerant of nutrient-poor, shallow soils. The heath communities of Australia are regarded as being among the most species rich plant communities in the world and over 750 species have been recorded for coastal heaths around Sydney of which the study area is representative (Fairley and Moore, 1989).

Figure 3.4. Photograph illustrating the extent of sheet erosion on a gentle slope at the edge of a plateau area.

No ash layer was found in the heathland by the time of our first visit but relatively large charcoal fragments were still present among the remaining stems of plants and in divots in the soil. Sedimentation due to erosion by water was observed in many areas and examination revealed that ash deposits formed the initial layer of post-fire sedimentation. Erosion by wind is also believed to have contributed to the loss of some soil and the initial ash layer in this area.

This landscape appeared to be slower to recover and was deemed to be more accessible for experimental work. Some erosion had already taken place by the time the first visit was made. Minor sheet erosion could be observed in most areas. Figure 3.4 shows obvious signs of sheet flow and erosion. This photograph was taken approximately 8 weeks after the fires in the transitional zone between heathland and forest-terrace.

Figure 3.5. Photograph of the organic crust which provides significant protection from sheet erosion in this environment.

3.3 Soil Surface Attributes in Royal National Park

3.3.1 Organic Crusts

Much of the soil was covered by an organic crust which appeared to be protecting the surface from erosion. Organic crusts can perform important functions in protecting the soil in a similar manner to other forms of soil cover (Eldridge, 1996; Greene *et al.*, 1990; see also Section 2.4.3). Figure 3.5 shows a severely burned site were the organic crust dominates the level of soil cover.

Figure 3.6. Photograph illustrating the severity of the water repellent layer which was found to be very widespread and persistent.

3.3.2 Water Repellence

As the majority of soils in the area are coarse textured sands (Walker, 1960), infiltration of rain was not expected to be a problem. However, the apparent abundance of sheet flows, even after the mild rain events that had occurred after the fires, indicated that inhibition of infiltration was occurring.

As similar soils have been shown to be water repellent, water repellence was suspected in this case as well. Testing, using the method outlined in Section 4.2, showed that water repellence was severe and very widespread. Figure 3.6 illustrates the severity of the water repellence which was found to occur as a layer of about 10 to 15 cm thickness, beginning at or just below the loose sandy layer covering parts of the soil surface. Water repellence was therefore assumed to be a major factor in the generation of runoff in this environment.

3.3.3 Litterdams and Microterraces

Contributing to the overland flow were also large areas of bare parent rock and terrace benches were soil water was exfiltrating. As mentioned, the level of sheet erosion appeared to be minor and the soil surface remained stable. This was attributed partly to the organic crust and the dense rootmat which had persisted following the fires. The soil itself lacked in cohesion and aggregation. Also, the slopes of these areas are gentle (less than 5 per cent) which reduces the potential erosivity of any runoff that occurs. Under these conditions, small debris dams commonly formed between the base of plant stems. These dams, commonly referred to as *litterdams and micro-terraces*, have been described in detail by Mitchell and Humphreys (1987). The debris dams cause overland flow to spread evenly across slopes in a cascading fashion. This inhibits the formation of concentrated flows which could potentially elevate the level of erosion significantly (Eddy *et al.*, 1996; Paton *et al.*, 1995). Figure3.7 shows some microterraces observed in the general study area.

3.3.4 The Effects of Tracks on Overland Flow

The effect of artificial concentration of the sheet flow can be observed along tracks, trails and fire-breaks. Many of these tracks were constructed as part of previous fire fighting activities simply be clearing the vegetation and scalping away the top layer of soil. Some repair work had been done and drainage installed but these areas are subject to severe degradation by concentrated flow. Figure 3.8 shows part of the lower Big Marley Trail which is subject to erosion caused by the interception and channelling of sheet flows generated on the heathland slope on the right side of the photograph. This slope is the area where the experiments described in the following chapter were carried out and is also depicted in Figure 3.2 as the *Coastal Heath* representative landscape.

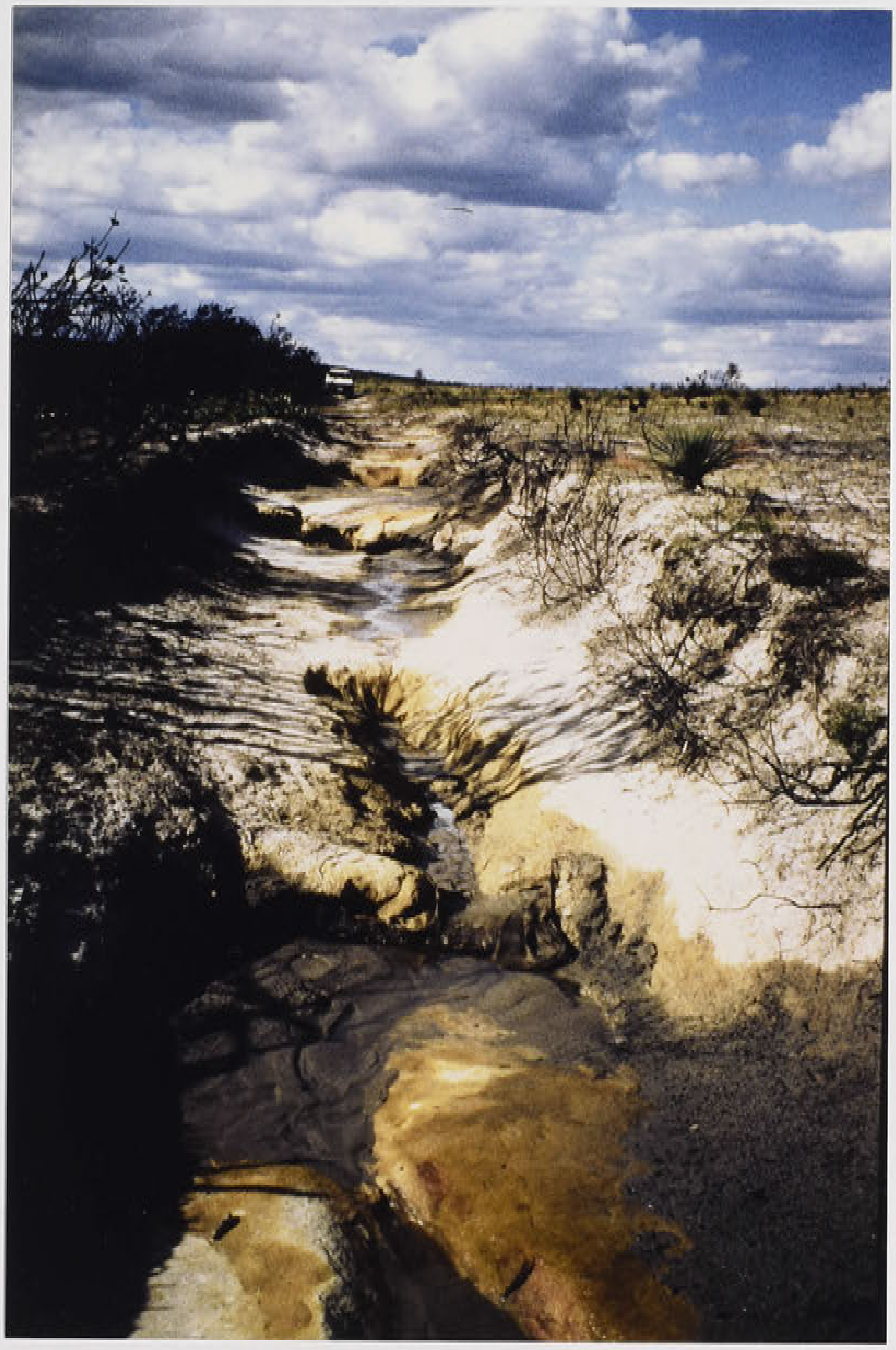
Figure 3.7. Typical microterraces and litterdams in Royal National Park. This photograph depicts the spreading effect of the debris dams: water flows are concentrated between the sandstone outcrops in the back of the picture and are spread across several metres by the time the flows have reached the foreground

Fire trails and walking tracks have been identified as one of the main erosion problems in national parks and other reserves. In Royal National Park it appears that these tracks would be subject to some erosion even without the effects of fire but that the rate of erosion is increased due to the additional overland flow generated on the fire affected slopes. It is expected that the generation and rate of overland flow would decrease as the vegetation regenerates and litter levels build up. A change in the persistence and severity of water repellence could also be expected as a litter mulch would increase the moisture status of the soil which reduces the impacts of hydrophobicity (see also Section 2.4.2). This has been observed following the Ash Wednesday Fires in Victoria (Leitch *et al.*, 1983).

3.4 Development of Strategy for Study

For the above reasons it was decided to concentrate our efforts in the coastal healthland. The site that was chosen for experimental work is located on a west- to southwest-facing heathland slope behind clifftop dunes in the north-eastern section of Royal National Park (Figure 3.1). The observations and hypotheses described above were used to develop a strategy for this study. Consequently, the first set of experiments which are described in the following chapters was carried out during the 11 to 22 May, 1994. As the fires had occurred during early January (concluding on the 14 January) the experiments and measurements are therefore not representative of immediate post-fire conditions. Also, the recovery of the study area to pre-fire condition was expected to be longer than the time available for this project.

Figure 3.8.
A section of the Big Marly Trail subject to erosion by concentrated flow. Sheet flow generated on the slopes at the right hand side of the photograph are channelled along the track resulting in severe degradation of the track and areas which receive drainage from extended sections of track.



The following photograph (Figure 3.9A) illustrates the extent of recovery at the time of the first set of rainfall simulation experiments (May, 1994) while the second photograph (Figure 3.9B) was taken at the time of the second set of experiments in April / May 1996.

Figure 3.9A (above). Photograph of study site illustrating the level of post-fire recovery taken in May 1994, approximately 4 months following the Sydney Fires.

Figure 3.9A. Photograph of study site illustrating the level of post-fire recovery taken in April 1996, approximately 28 months after fire.

3.5 Description of the Study Site

The area of the study site is part of a large coastal plateau named and described by Pidgeon (1937), extending about 25 kilometres inland and 40 kilometres along the coastline The pre-fire-vegetation consisted of sclerophyllous heath and grassland. Walker (1960) carried out a detailed soil landscape survey of the area which includes descriptions of this vegetation type and its range. A description of the soil present at the study site is given in below.

Soil profile description

Gradual texture profile; surface covered by organic, peaty crust in places - especially around the base of plants some of which has been partly burned, soil material structureless with no lime accumulation.
Parent material consists of strongly mottled laterite and sandstones.

Depth (cm)	Horizon	Description	Comments
0			
	A1	dark grey loamy silt	organic crust present
10			
	A2	yellow-grey brown loamy sand to loamy silt	mottling, iron rust, slightly heavier than A1
25			
	B1	yellow-light grey clayey sand	mottling, iron rust
75			
	C	very light grey clayey sand	heavy mottling, quite wet, very solid and hard to dig
75+			

The area has a humid temperate climate with mean annual precipitation of 850 mm. Rainfall is fairly evenly distributed throughout the year with summer being the wettest season and winter the driest. Table 3.1 gives the average annual rainfall distribution for the study area.

Table 3.1. Average Annual Rainfall Distribution for Study Area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Average Rainfall (mm)	102	86	110	72	62	79	33	53	44	68	70	71	850

Chapter 4

Methodology

4. Methodology

The experiments carried out as part of this study investigated the response of hillslopes to simulated rainfall applied at different times following fire. Runoff and related soil erosion driven by rainfall and overland flow were measured for a range of rainfall intensities which were applied using a portable rainfall simulator. Some limited monitoring of responses to natural rain was also carried out. This component only contributed qualitative observations.

Besides field measurements of water repellence, two sets of rainfall simulator experiments were conducted. The first was conducted as soon as practical which was at 4 months after the fires. The second was conducted approximately two years after the first set of experiments, that is at 28 months after the fires. By comparing the results of the two sets of experiments, the influence of the natural recovery of the soil and vegetation on erosion processes activated by fire could be partially assessed.

4.1 Observations and Development of Hypotheses

Following initial inspection of the burned areas, several observations were made and issues identified that may be worthy of investigation. These are summarised below:

1. areas that were burned but otherwise undisturbed showed signs of overland flow and sheet erosion but rill erosion was observed only rarely,

2. tracks, trails and similar areas showed signs of severe degradation by rill and gully erosion and sedimentation, and

3. water repellence at the soil surface was very extensive and measured at a limited number of sites using an adoption of Water Drop Penetration Time and ethanol testing (Crockford *et al.*, 1991) which showed water repellence to be severe in all areas other than moist drainage lines and depressions.

These observations were made following natural rainstorms. The intensity or duration of the rain events were unknown but discussion with park rangers indicated that no severe falls had been witnessed. These observations lead to the following hypotheses:

1. The natural, post-fire soil surface is resistant to erosion and incision by raindrop impact and overland flows produced by patterns of average rainfall in this environment. Extreme rainfall events (say with recurrence intervals of greater or equal to 100 years, ie. 110 mmh^{-1} for 30 min in this area) are required to initiate severe degradation of the fire affected soil surface in this landscape.

2. The generation of sheet flow has been changed by the fire due to the loss of soil cover and reduction in infiltration rate.

3. Regeneration of plant cover will reduce the rate of overland flow and soil loss.

4. The interception of sheet flows generated on the fire affected areas by tracks results in catastrophic erosion.

5. The effect of water repellence on infiltration has been altered by the fire. Regeneration of plant cover, accumulation of litter and breakdown of hydrophobic substances will reduce the effect of water repellence over time.

The experiments described below were designed to test hypotheses 1., 2. and 3. and provide some baseline data on runoff and erosion rates for the study area and similar landscapes which would assist in evaluating hypotheses 4. and 5.

To test these hypotheses, a study was designed based around the use of a rainfall simulator. A rainfall simulator was used because:

- using plot experiments gave a holistic simulation of erosion processes on a slope scale,

- scenarios of combinations of rainfall events and surface condition can be tested using this approach,

- the experimental design was relatively simple and tractable within the available time and resources, and

- the effect of natural regeneration processes on soil water repellence over time could be evaluated by using a plot with a wetting agent (or surfactant) as control, thus separating the effect of water repellence on infiltration under rainfall over time from other factors such as soil crusting.

4.2 Determination of Water Repellence

Indications of the presence and perseverance of soil water repellence were obtained using the Water Drop Penetration Test (WDPT) and the ethanol test devised by Letey (1968) reported in various, but slight variation in the literature (Bisdom *et al.*, 1993; Crockford *et al.*, 1991; King, 1981; Watson and Letey, 1970; Letey 1968).

The WDPT simply involves placing a drop of water on the surface to be tested and recording the time until infiltration occurs. Table 4.1 shows the classification used for WDPT. In a *severely* water repellent soil, infiltration does not occur and the water will evaporate before it enters the soil in liquid form. The cut-off time chosen for testing water repellence was initially 30 minutes, but reduced to 10 minutes (600 seconds) due to the laboriousness of the task and apparent consistency of results obtained.

Table 4.1. Classification of Water Repellence According to Water Drop Penetration Time (after Bisdom *et al.*, 1993)

WDPT (s)	Classification
< 3	Wettable
3-60	Slightly water repellent
60-600	Strongly water repellent
> 600	Severely water repellent

The ethanol test involves the application a water and ethanol mixture to the water repellent surface. The concentration of ethanol is increased until the solution infiltrates within a given time period. The test time chosen was 3 seconds based on the reported experiences of Crockford *et al.* (1991). Indices for comparing levels of water repellence based on a combination of this test and the WDPT test were developed by Watson and Letey (1970). These indices supplement the water drop penetration test only which alone does not differentiate between infiltration and evaporation over long periods. Watson and Letey (1970) proposed the indicy should consist of the *90°-surface tension* (γ_n), which is derived by plotting the cosine of the apparent liquid-solid contact angle (θ) versus the liquid surface tension (measured in dynes per cm) and using the cos θ intercept. This can be approximated by using the surface tension of the aqueous ethanol solution which has a 3-second-WDPT. For simplicity, the values given in this study are the percentages of ethanol in water rather than the surface tension. Pure water has a surface tension of 72.1 dynes cm^{-1} and pure ethanol has a surface tension of 21.9 dynes cm^{-1}. The results of the water repellence testing are reported in Section 5.1 and Appendix I.

4.3 Materials and Methods

In this section the experimental methodology used is described. The overall methodology was to test the response of the soil surfaces at the study site using the rainfall simulator at two times during the post-fire recovery period: four months, and 2 years and four months after the fires. The influence of water repellency was examined by applying a wetting agent to half of the plots tested.

Twelve 1.5 m wide x 6m long erosion plots (slope 5.2 ± 0.9 %) were selected side-by-side, along a relatively uniform slope immediately above Big Marley Trail for ease of access. The plots were divided into 3 blocks of four (or two pairs each). Treatments were assigned at random between the subsets which means that each treatment was replicated 3 times. A summary of the experiments is given in Table 4.2 below.

Table 4.2. Summary of Rainfall Simulation Experiments

Block	Year	Treatment	Rainfall Intensity (mm hr^{-1}) Low(1)	Low(2)	Medium(3)	High(4)
1	1994	wetting agent	45	45	70	95
		hydrophobic	45	45	75	120
	1996	wetting agent	22	30	45	73
		hydrophobic	35	43	87	116
2	1994	wetting agent	48	51	81	#
		hydrophobic	48	48	83	126
	1996	wetting agent	49	56	91	116
		hydrophobic	47	46	82	102
3	1994	wetting agent	49	48	79	120
		hydrophobic	49	48	77	119
	1996	wetting agent	56	58	95	151
		hydrophobic	55	54	90	148

\# no run due to water shortage

Design intensities were:

Low(1&2):	1in1 Year Annual Return Interval:	44 mmh^{-1} for 30 minutes.
Medium(3):	1in10 Year Annual Return Interval;	75 mmh^{-1} for 30 minutes.
High(4):	1in100 Year Annual Return Interval;	110 mmh^{-1} for 30 minutes.

Values calculated from Australian Rainfall and Runoff (Pilgrim, 1987).

Note: The Block1-1996-wetting-agent-plot was affected by pressure problems with the pumping system. Consequently the intensities for this plot were lower (medium same as low and high same as medium for other plots). The low, medium and high categories were however retained for these runs because of the sequencing and experimental layout.

Two experimental runs at low rainfall intensity were applied, followed by a medium and then a high rainfall intensity. There was considerable variation in average rain intensity (Section 4.2.1) which was taken into consideration in the analysis (Section 5.3). An initial low intensity run was used to pre-condition the plot for the following, sequential experiments. This technique is commonly used (Meyer and Harmon, 1985) to allow for the comparison of runoff and erosion rate off the initial surface with that affected by the sequencing of runs. For example a surface that has not been subjected to rain for some time may have a store of loose soil on the surface due to animal activity (burrowing, trampling). This soil is easily washed away in the first runoff event and would affect the comparison of the erosion rate recorded using a single low intensity event only with that of the higher intensities. Using two sequential low intensity runs allows for evaluation of the magnitude of this effect.

The following procedures were followed during each set of experiments and are described in more detail below. The water repellence testing was carried out independently on an area adjacent to the erosion plots which was similar in soil type, slope, aspect and vegetation cover. An adaptation of the methodology of Crockford *et al.* (1991), described in Section 4.2.1 was used. The results are reported in Section 5.1 and Appendix I. The water repellence testing was carried out to determine whether changes of water repellence over time could be detected. The procedure for the erosion experiments was:

1. The plots were surveyed so that the longer (6 metre) boundaries were approximately at right angles to the contours of the slope. The steel plot edges were inserted to define the plot to avoid accidental trafficking and the loss of runoff and splash from the plot during the experiments (Section 3.3.3).

2. The runoff collection system was installed and the rainfall simulator carried over the plot, tied down and the water supply and recirculation system connected. The windshields were placed to maximise protection from wind and avoid drift of applied rain away from the plot (Section 4.3.3).

3. The plot was then pre-treated with wetting agent, or water only, depending on its designation (assigned randomly between pairs). The rainfall simulation experiments commenced within 5 minutes of this pre-treatment (Section 4.3.2).

4. The rainfall simulator was then turned on at the pre-set sweep rate and nozzle pressure to obtain the first (low intensity) event. Observations of the time to ponding and runoff were noted. Runoff was measured continuously and sediment sub-samples were taken; 6 per plot where possible (Section 4.3.4).

5. At the end of the first run, the runoff collection vessel was emptied and water reservoir replenished. Samples were packed away and new sample containers prepared. This caused a delay of 5 to 10 minutes after which the second run was commenced. The procedure described in point 4 was then repeated for the consequent runs. The sweep rate was adjusted for third and fourth runs to obtain the higher intensity rainfall.

6. The rainfall simulator was moved to the next plot completion of the final (4th) run. Vertical photographs of the plot surface were then taken for projected soil cover (Section 4.3.5). All standing vegetation and sticks more than approximately 10 mm above the surface were then removed and the surface photographed again to record contact cover. This was done so that the impact of projected and contact cover on erosion could be compared in the analysis (Section 5.2 and 5.3).

A sub-set of the sediment samples was analysed for particle sizes of the eroded sediment after completion of all the rainfall simulation runs The aggregate size distribution of the selected sediment samples were determined using a hand sieving technique, applied according the principles set out in Kemper & Rosenau (1986) . The sieve sizes used were 2000, 1000, 500, 250, 125, and 63 micron. Sieving was performed by hand for one minute in water taken from the same water supply used for the simulated rainfall. A further split was obtained at 22.1micron using the pipette technique also described in Kemper and Rosenau. Adjustments for water temperature and related viscosity effects were made.

This was done to provide a comparison of the aggregate size distribution of eroded sediment with that of the original soil. The original soil was analysed using the same technique. The results of this analysis is provided in Appendix IV.

4.3.1 Plot Pre-treatment with Wetting Agent

A commercially available soil wetting agent, *Aqua Soil Wetter* was applied to the selected plots immediately before the first simulated rain was applied. The method of application was that prescribed on the label. This involved applying 45 mL of wetting agent diluted in 9 Litres of water evenly over the 9 m^2 plot. Figure 4.1 shows the diluted wetting agent being applied uniformly over the plot using a watering can with a herbicide attachment. Plots not subjected to wetting agent were pre-treated with an equivalent volume of water only. The treatment was applied approximately 5 minutes before the first rainfall simulation runs commenced.

The wetting agent was selected before the experiments from a range of wetting agents found in local stores. Each of the wetting agents was tested on soil samples that had been collected using water drop penetration time. The wetting agent used was found to be the most effective in reducing the effect of water repellence on infiltration for this soil. The laboratory tests indicated that this surfactant apparently eliminated the effect of water repellence as water drop penetration was instantaneous.

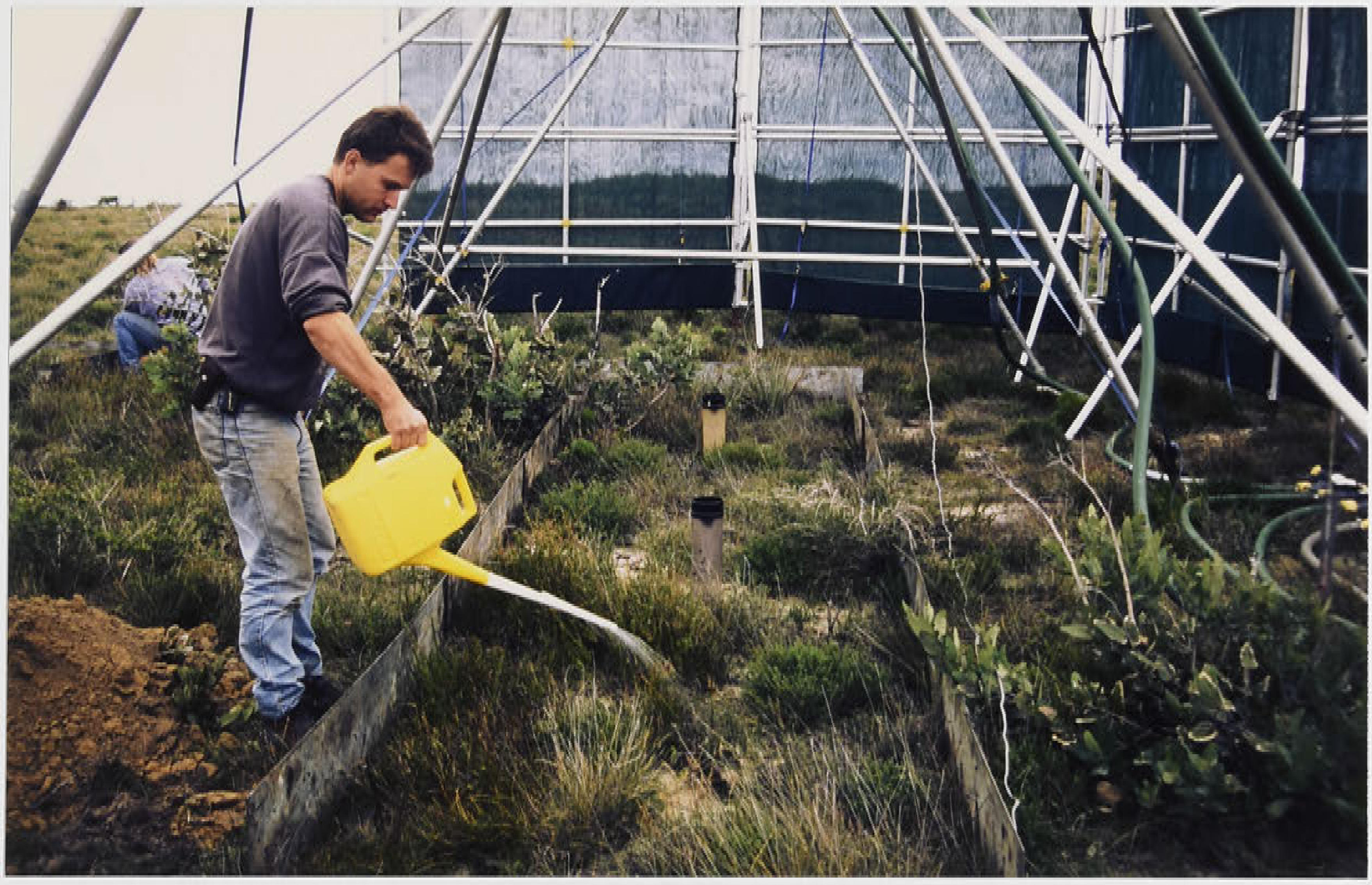


Figure 4.1. Application of the wetting agent one of the erosion plots prior to the rainfall simulation experiments.

The use of a surfactant for treatment for bushfire affected areas is not considered to be a viable management option in this environment. As indicated previously, the wetting agent was used to provide a means of detecting changes in water repellence over time as opposed to changes in infiltration rate due to all combined factors.

4.3.2 Plot Preparation, Rainfall Simulation and Runoff Collection

Galvanised steel sheets (5 mm thick x 120 cm long x 40 cm high) we used to define plot boundaries. The sheets were driven into a pre-cut grove to a depth of about 10 cm along the top and side boundaries. The grove was cut to a depth of 5 cm using a concrete saw and the plot sides were sharpened along their lower edge to facilitate entry into the soil.

The lower boundary and runoff collection trench were defined by a 5 mm x 150 cm x 15 cm galvanised steel sheet with a downslope facing sill or lip. This sheet was driven into the ground so that the top edge was level with the soil surface. Following the placement of the lower boundary, a trench of about 10 width x 10 cm depth was excavated and slanted (about 2-3°) to one side to accommodate the runoff collection trough. This trough consisted of a 5mm x 150 cm x 20 cm galvanised steel sheet which was bent to a V shape. The trough was placed in the trough with the upslope edge fitting underneath the lower plot boundary sill.

Figure 4.2 shows the trough spilling the runoff captured into a small collection basin which was fabricated from a plastic butcher's bin (40 cm wide x 60 cm long x 40 cm deep). This basin was equipped with a fitting that allowed the water to be sucked to a runoff collection sampler using a large vacuum cleaner. The collection basin was primed prior to each run, that is it was filled with water up to the level where the vacuum hose was extracting water into the runoff sampler.

The runoff collection sampler consists of three evacuated vessels; one with several compartments increasing in volume to allow high resolution measurement of the initial runoff and two large tanks which are filled alternately while the other is being drained. Figure 4.3 shows the compartments of the first tank, the other two are located behind and obscured from view. The level of runoff in each tank is recorded manually at 30 second intervals allowing runoff volume and rate to be calculated.

The simulated rainfall was applied using the CSIRO Division of Soils Field Rainfall Simulator (Figures 4.4A & 4.4B). This rainfall simulator is a sweeping nozzle type simulator based on a design by Meyer and Harmon (1979) and further developed by CSIRO (Hairsine and Carrigy, in prep.). The design intensities are given in Table 4.1 above and were applied to each plot

Figure 4.2.
Plot end runoff collection trough and collection basin used during the rainfall simulation experiment.

consecutively with a break of 5 to 10 minutes between runs. The simulator was fitted with 80100 Veejet nozzles and used at 70 kPa to obtain a median drop diameter of 1.2 mm (Hairsine and Carrigy, in prep.).

Due to water shortages, wind and other factors, some variation in run length and rainfall intensity occurred. Two rain gauges on each plot were used to monitor the rain applied to each plot during the simulations. The actual rainfall intensity applied to each plot was then calculated using the observed values (Table 4.1). The run duration was standardised for the statistical analysis (Section 5.3) by using only the first 20 minutes of the rainfall simulations. The maximum run length was 30 minutes while only one run was shorter than 20 minutes at 17 minutes but as this was a treated plot and no runoff was generally observed of these plots until the third (medium intensity) event so the effect is assumed to be negligible.

To reduce the effect of wind, wind shields were erected. This consisted of aluminium scaffolding covered with layers of shadecloth to provide a semi-permeable barrier. The shields were moved for each run to optimise shelter from wind and ensure even coverage of plots by the simulated rain.

Figure 4.3. Runoff sampler used during the rainfall simulation experiments.

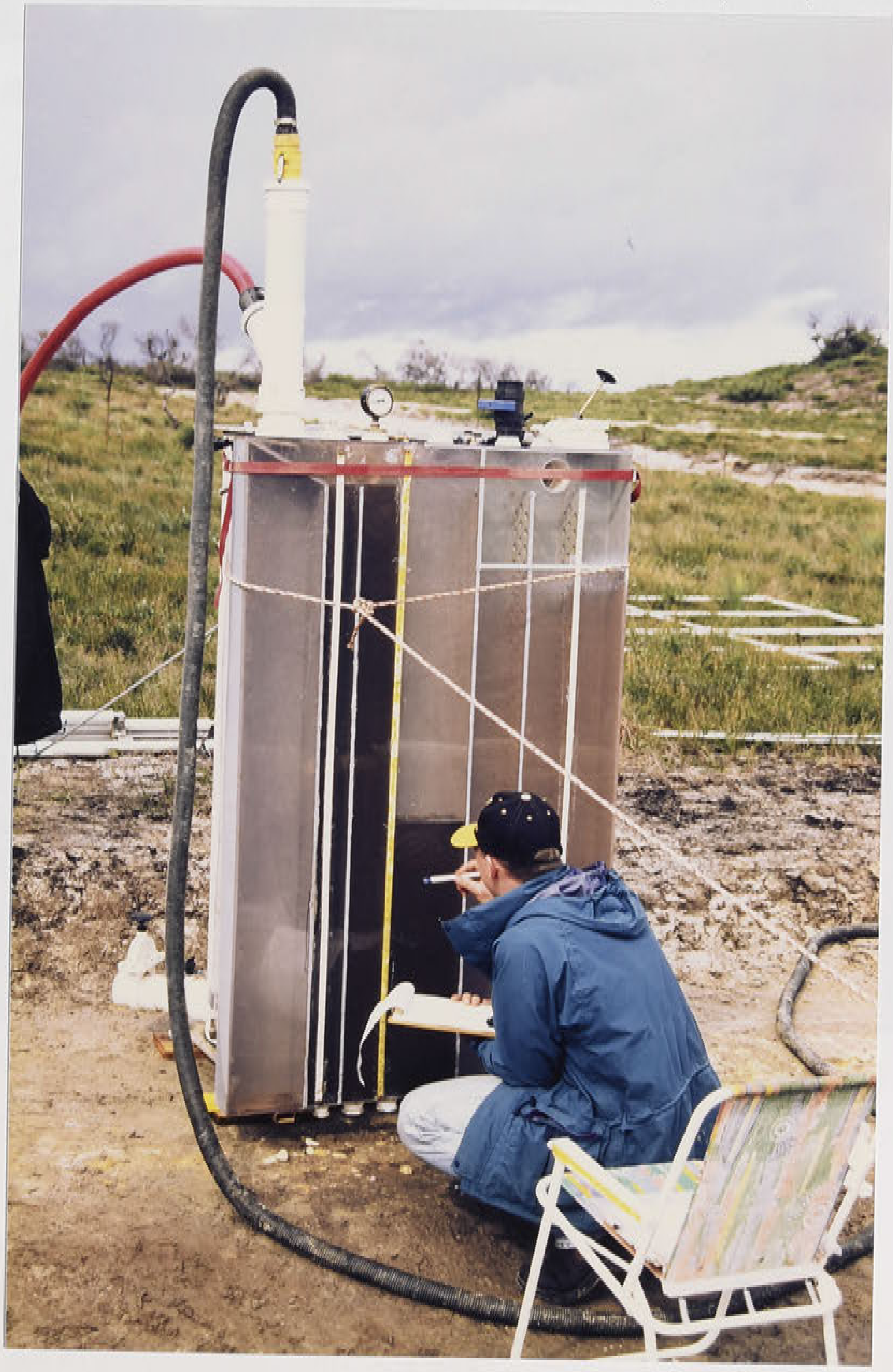


Figure 4.4A (above). Photograph showing the field rainfall simulator used during the erosion experiments.

Figure 4.4B (above). Another view of the field rainfall simulator used during the erosion experiments.

4.3.3 Sediment Sampling and Processing

Six sediment samples per run were taken at evenly spaced intervals. The samples were collected by placing a jar under the end of the sediment collection trough, above the collection basin (Figure 4.2). The time and duration of each sample were recorded. The duration of sampling depended on the runoff rate but generally ranged from 4 to 20 seconds, so to obtain a water and sediment sample of the order of 0.5 to 0.8 litres.

The volume of sample collected was determined by measuring the height of water in the jar and using a calibration relationship between depth and volume for each type of container. The samples from Plots 94A1, 94A2, 94B1, 94B2, 96A1, 96A3, 96B1 and 96B3 (refer to table 5.2 for plot designation) were then oven dried at 105° Celsius and weighed. The results of this analysis are summarised in Section 5.2 (Table 5.2) and given in detail in Appendix IV.

The samples from plots 94A3, 94B3, 96A2 and 96B2 were processed for sediment aggregate size distribution by wet sieving and pipette sampling. Sieve and pipette fractions used were >2.000 mm, 2.000-1.000 mm, 1.000-0.500 mm, 0.500-0.250 mm, 0.250-0.125 mm, 0.125-0.063 mm and 0.063 to 0.021 mm. The samples were decanted into the sieves in a water bath. The sieving was carried out manually for approximately 2 minutes in an up and down motion. The sieves were then removed and separated and the sieve fractions flushed into beakers with a wash bottle. The pipette sample was taken from the residual sample in the water bath. After the sieves were removed from the bath, the residual was stirred to thoroughly mix the residual (<0.063mm). When the visible swirling had stopped timing began and depending on water temperature (18-21°C) the pipette was inserted and the sample taken at a depth of 10 cm after about 4 minutes (the actual time was determined using Stokes Law with water temperature as an input). The results of this analysis are provided in Appendix IV.

The sieved fractions from the first set of experiments (plots 94A3 and 94B3) were also analysed for organic matter content to determine ash and charcoal contents. Visual examination of the samples indicated that there was very little organic particulate matter in the samples. The determination of total organics (including ash and charcoal) was achieved by weighing the oven dried samples (at 105°C), then transferring the samples into a furnace, heating at 550° Celsius for 1.5 hours and re-weighing. The results from this analysis indicated that there was only a small organic component in the sediment collected (as determined by mass) and are given in Appendix V. The observed ash and charcoal fragments were apparently too light to contribute significantly to the mass of sediment which was measured at a resolution of 0.005±5 grams. The sediment collected during the second set of experiments was similar in appearance to those of the first set. Organic matter content analysis was not undertaken for these samples.

4.3.4 Measurement of Soil Cover

Soil cover was recorded using colour photographs taken with a camera mounted on an aluminium frame about 3 metres vertically above the soil surface (Figure 4.5). Two 1m x 1m areas were photographed on each plot, one directly above the lower plot boundary and one selected at random. The surfaces were photographed after conclusion of the experiments, then all non-contact soil cover (cover not within 10 mm of the soil surface)was removed and the surfaces were photographed again. Removal of projected cover was done by clipping all standing vegetation and dead stalks or sticks using electric and hand shears a few millimetres above the soil surface. Loose litter, cut stems and leaves were then removed by hand or using a vacuum cleaner.

Figure 4.5 (left). The camera set-up used to obtain vertical photographs of the soil surfaces for cover analysis.

The photographs were then scanned to provide a digital image. The images were then analysed using the technique developed by Huang and Moran (1995). In this technique representative pixels are selected manually to provide colour definitions or *component classes* that correspond 100% with either cover or soil. A computer program is used to calculate the percentage of the image that corresponds to the selected classes ie. cover or exposed soil. Figure 4.6A shows a scanned photograph of projected cover on one of the plot surfaces. Figure 4.6B shows the same area after clipping, and Figure 4.6C and Figure 4.6D respectively show the processed images after component classes have been assigned. Note that this process is interactive so that comparison of the actual photographs and the classified images may be used to adjust classes until visual interpretation is satisfied.

The organic crust (Chapter 3) was classified as cover as it protects the surface in the same way as other forms of cover.

The data obtained from this analysis is summarised in Table 5.3 (Section 5.2).

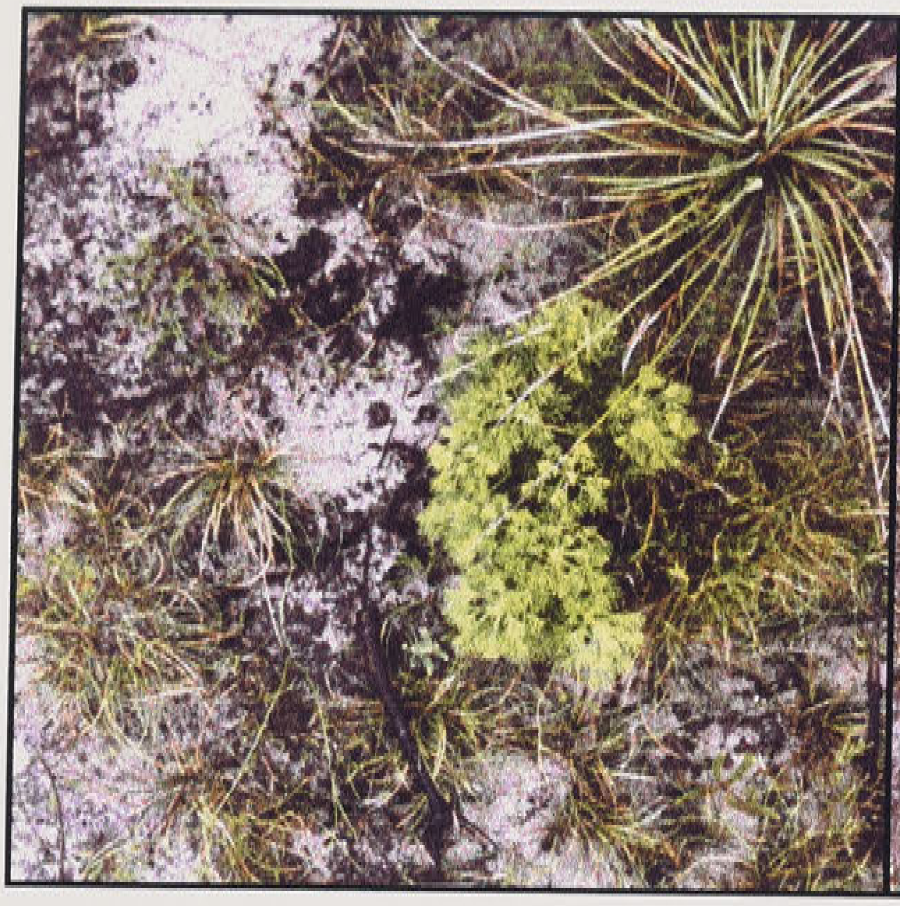


Figure 4.6A. Scanned section of the original vertical photograph of a 1996 plot surface (28 months after fire) taken for analysis of projected soil cover.

Figure 4.6B. The same surface as depicted in Figure 4.6A after clipping and removal of projected (non-contact) cover.

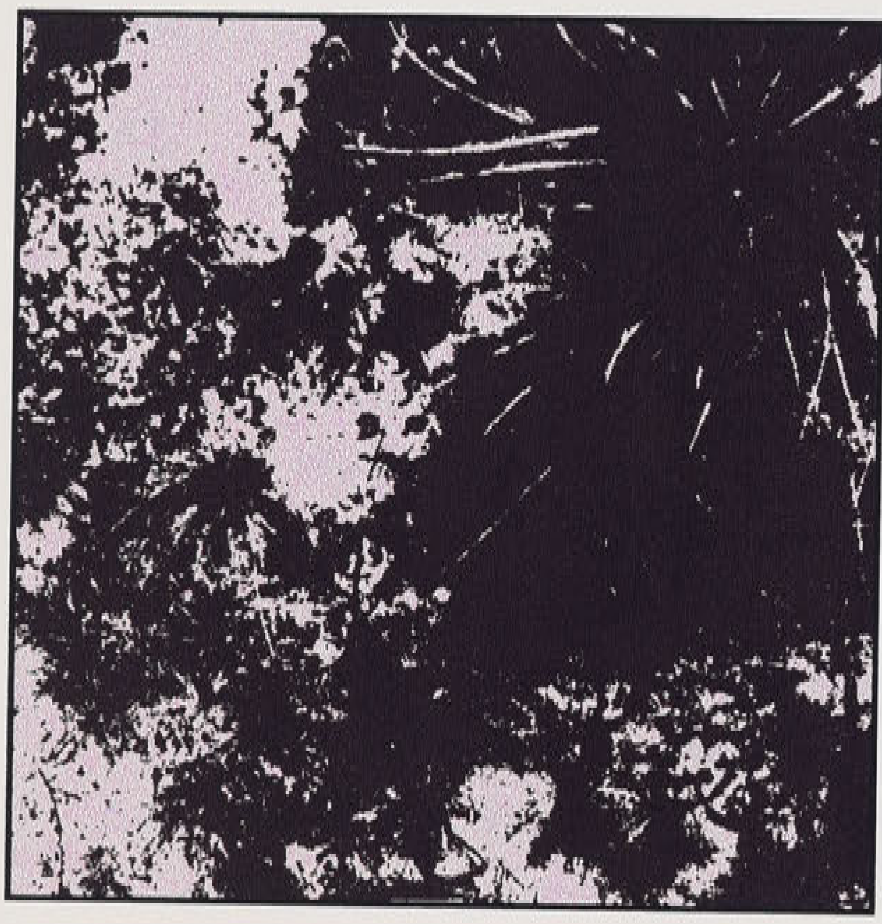


Figure 4.6C. The processed image of Figure 4.6A. Black denotes the cover including the organic crust while white represents the exposed soil surface.

Figure 4.6D. The processed image of Figure 4.6B. Black denotes contact cover while white denotes the soil surface. For these two images, the cover level is almost identical because of the extend of the organic crust.

Chapter 5

Results

5. Results

In this chapter, the results of the field rainfall simulations are presented and analysed. Additional data are contained in the appendices as indicated. The effects of wetting agent treatment, rainfall intensity and soil cover on runoff and sediment yield are examined. The overall behaviour of the soil, water and vegetation system is discussed in Chapter 6. This chapter also gives the data obtained from the water repellence monitoring.

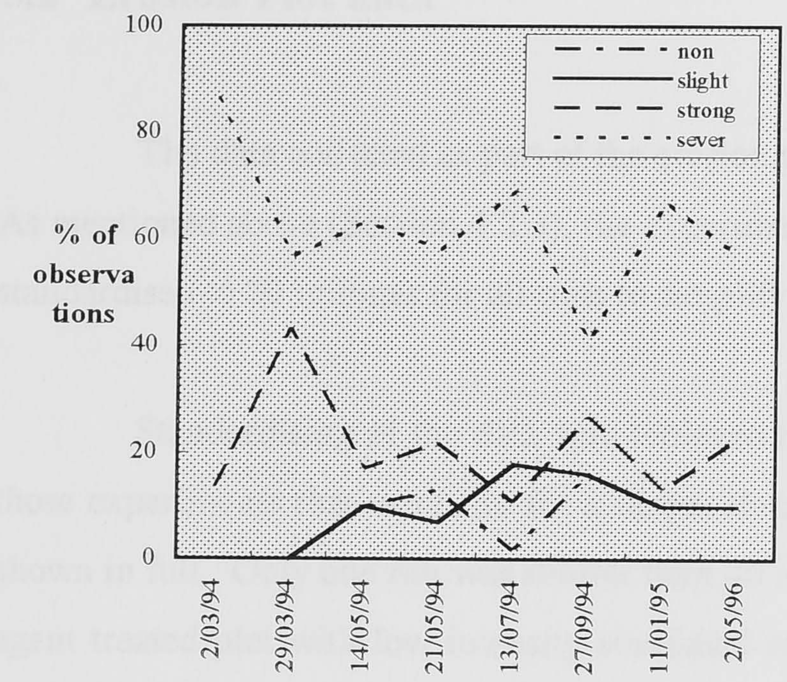
5.1 Water Repellence Monitoring

Water repellence was measured to be only slightly variable across the area tested but varied with soil depth. Water repellence fluctuated over time but there was no systematic variation in water repellence which indicates that the two year recovery period did not reduce water repellence.

The data from the Water Drop Penetration Time (WDPT) tests indicated water repellence of the upper layer of soil was severe (> 600 seconds) in most areas. Around the base of plants the water repellence ranged from strongly water repellent to severely water repellent (330 - > 600 s). The depth of the severely water repellent soil layer varied from 50 mm (mostly around plants) to 150 mm. The soil below this layer was found to be slightly to strongly water repellent. The soil below 250 mm was found to be wettable. A summary of the data from the water repellence testing is provided in Figures 5.1A and 5.1B, and Table 5.2 below. Statistical evaluation of this data was confined to a comparison of means and standard deviations for the number of observations for each water repellence rating. The data were grouped according to time and soil depth. The large standard deviations indicated that there were no trends in this data. The means and standard deviations for the water repellence testing are given in Table 5.1. The raw data for the WDPT is given in Appendix I.

Table 5.1. Evaluation of Water Repellence Measurements.

		% of Observations			
		Wettable	**Slightly Water Repellent**	**Strongly Water Repellent**	**Severely Water Repellent**
Over Time	**Mean**	8	9	21	62
	Standard Deviation	6	7	11	13
With Soil Depth (see Fig. 5.1b)	**Mean**	19	33	14	35
	Standard Deviation	33	43	18	40



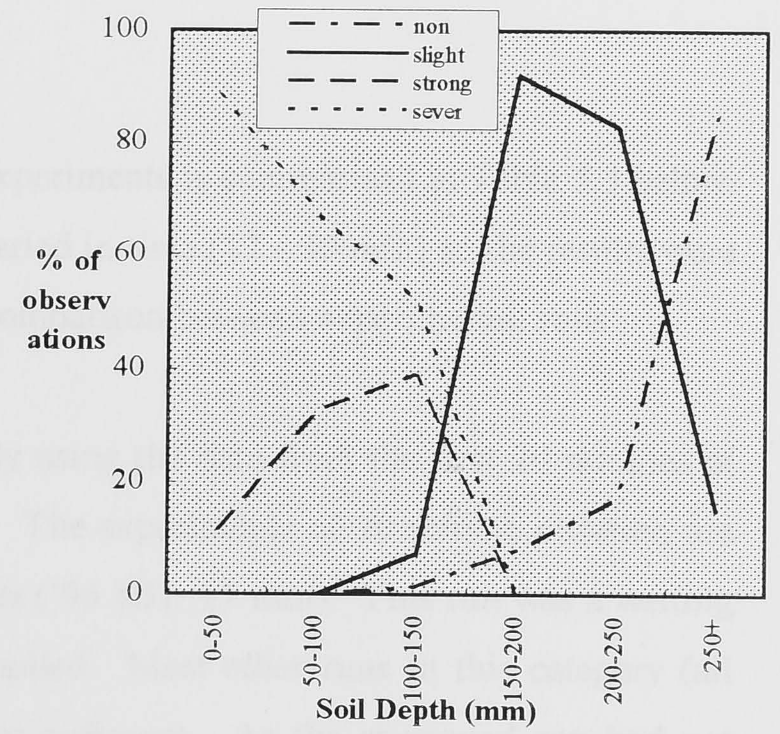


Figure 5.1A. Trend in water repellence over time (Note: time intervals of measurement are not equal and first two dates comprise 30 samples to 150 mm only).

Figure 5.1B. Variation in soil water repellence with soil depth for all observations.

Table 5.2. Results from Water Repellence Measurement

Date	WDPT number of observations (depth in mm) wettable	slightly WR	strongly WR	severely WR	Aqueous Ethanol %	Comments
2-Mar-94	0	0	4	26		limited testing (no ethanol), tested to a depth 150 mm only
29Mar-94	0	0	13 (0-150)	17 (0-150)	-	limited testing (no ethanol), strongly WR for organic crust, bare soil -severe WR,
14May-94	10 (250+)	10 (150-250)	17 (0-150)	63 (0-150)	0-50	strongly WR around plants (organic crust)
21May-94	13 (200+)	7 (150-200)	22 (0-150)	58 (0-150)	0-50	wettable at & below 200 mm - moist at 250 mm, strongly WR around plants (organic crust)
13July-94	2 (250+)	18 (150-200)	11 (0-150)	69 (0-150)	0-40	soil drier than last time,
27Sept-94	16 (150+)	16 (50-150)	27 (0-150)	41 (0-150)	0-30	soil quite moist below 100 mm, recent rain evident,
11Jan-95	10 (250+)	10 (150-250)	13 (0-150)	67 (0-150)	0-40	soil quite dry, hot weather conditions,
2May-96	10 (250+)	10 (150-250)	23	57	0-30	cool condition but soil fairly dry,

Note: Spacing of samples across the area was at random but measurements were carried out at least 1 metre apart.

5.2 Erosion Plot data

The data collected as part of the erosion plot experiments is summarised in Table 5.3 below. As mentioned above (Section 4.2.3), the experiments varied in time (17 - 30 min) so the results were standardised to 20 minutes for all runs to simplify the comparison between experimental runs.

Standardising of the data was achieved by only using the data from the first 20 minutes of those experiments that were run for a longer duration. The experiments of 20 minute duration are shown in full. Only one run was shorter than 20 minutes ('96 1B1: 17 min). This run was a wetting agent treated plot with low intensity simulated rain applied. Most other runs in this category (all designated *B1 and *B2) yielded little or no runoff or sediment. As the shortened run had not produced runoff at the 17 minute stage, it is assumed that extrapolation to 20 minutes will not significantly affect the outcome of the analysis.

A more complete version of the data, including the non-standardised data-set is presented in Appendix III as runoff graphs. The runoff data was summarised for the analysis as total runoff, peak runoff rate and time to achieve peak runoff rate. The frequency of runoff sampling, at 30 second intervals, resulted in a large data set which is not reproduced here for practical reasons.

In summary, the depth of simulated rainfall applied to the 9 m^2 erosion plots ranged from 7 to 50 mm and produced total depths of runoff ranging from 0 to 31 mm with mean values of 23.8 and 7.5 mm respectively. Rainfall intensity varied between 22 $mmhr^{-1}$ and 151 mmh^{-1} with a mean of 71.5 mmh^{-1}. Peak runoff rate observed ranged from 0 mmh^{-1} to 16, with mmh^{-1} a mean of 37.4 mmh^{-1}.

Trends in this data are examined below. The statistical technique used was an Analysis of Variance as described below.

Plot & Run	Treatment	RAINFALL: Design Intensity	RAINFALL: Average Intensity mmh^{-1}	RAINFALL: Total depth applied mm	RUNOFF: Total depth collected mm	RUNOFF: Peak mmh^{-1}	RUNOFF: Time to Peak	SEDIMENT: Number of Samples	SEDIMENT: Mean Sediment Conc. (gL^{-1})	SEDIMENT: Mean Sediment Yield (g)	SEDIMENT: Mean Sediment Yield (tha^{-1})	COVER: Projected %	COVER: Contact %
1B1	wetting agent	low	45	15	0	0.29	960	no samples taken		0	0	53.0	50.0
1B2	wetting agent	low	45	15	0	1.83	1200	no samples taken		0	0	53.0	50.0
1B3	wetting agent	medium	75	25	9	34.53	1200	5	2.86	234.23	0.26	53.0	50.0
1B4	wetting agent	high	120	40	23	76.79	1200	6	2.36	482.16	0.54	53.0	50.0
1A1	hydrophobic	low	45	15	6	24.06	1110	6	3.00	157.45	0.17	59.5	46.0
1A2	hydrophobic	low	45	15	7	24.88	1080	6	1.83	112.52	0.13	59.5	46.0
1A3	hydrophobic	medium	70	23	11	40.42	930	6	2.30	232.36	0.26	59.5	46.0
1A4	hydrophobic	high	95	32	19	69.54	870	6	2.64	439.19	0.49	59.5	46.0
2B1	wetting agent	low	48	16	1	4.80	1080	no samples taken		0	0	56.0	53.8
2B2	wetting agent	low	48	16	0	0.16	840	no samples taken		0	0	56.0	53.8
2B3	wetting agent	medium	83	28	8	32.98	1200	6	1.61	122.52	0.14	56.0	53.8
2B4	wetting agent	high	126	42	24	88.39	1200	6	1.28	276.32	0.31	56.0	53.8
2A1	hydrophobic	low	48	16	4	20.26	1200	6	3.37	135.69	0.15	52.3	51.5
2A2	hydrophobic	low	51	17	7	24.76	1050	6	2.39	141.01	0.16	52.3	51.5
2A3	hydrophobic	medium	81	27	15	53.66	990	6	2.98	407.81	0.45	52.3	51.5
2A4	hydrophobic	high	* no run due to water shortage			-	-	-	-	-	-	-	-
3B1	wetting agent	low	49	16	1	4.68	1110	2	2.49	24.66	0.03	58.0	51.5
3B2	wetting agent	low	48	16	1	3.91	1200	3	1.65	15.72	0.02	58.0	51.5
3B3	wetting agent	medium	77	26	9	34.45	1050	6	1.98	156.21	0.17	58.0	51.5
3B4	wetting agent	high	119	40	20	75.38	1200	6	2.12	389.27	0.43	58.0	51.5
3A1	hydrophobic	low	49	16	5	22.31	1200	6	1.99	87.44	0.10	58.0	52.5
3A2	hydrophobic	low	48	16	6	24.21	1200	6	0.84	48.78	0.05	58.0	52.5
3A3	hydrophobic	medium	79	26	15	52.42	1200	6	0.92	120.91	0.13	58.0	52.5
3A4	hydrophobic	high	120	40	25	89.93	990	6	1.03	232.08	0.26	58.0	52.5

Table 5.3. Summary of Results from Plot Experiments (runs standardised to 20 minutes)
Part 1: May 1994 - approximately 4 months after fire.

Plot & Run	Treatment	RAINFALL Design Intensity	Average Intensity mmh^{-1}	Total depth applied mm	RUNOFF Total mm	Peak mmh^{-1}	Time to Peak	SEDIMENT Number of Samples	Mean Sediment Concentration (gL^{-1})	Mean Sediment Yield (g)	Mean Sediment Yield (tha^{-1})	COVER Projected %	Contact %
1B1	wetting agent	low	35	12	0	0.54	840	no samples taken		0	0	52.9	51.6
1B2	wetting agent	low	43	14	1	2.10	1200	no samples taken		0	0	52.9	51.6
1B3	wetting agent	medium	87	29	8	32.23	1170	6	0.79	59.65	0.07	52.9	51.6
1B4	wetting agent	high	116	39	17	62.97	1200	6	1.12	174.28	0.19	52.9	51.6
1A1	hydrophobic	low	22	7	4	18.08	1200	6	0.64	24.91	0.03	76.1	76.0
1A2	hydrophobic	low	30	10	6	21.93	1200	6	0.49	24.78	0.03	76.1	76.0
1A3	hydrophobic	medium	45	15	12	42.73	1170	6	0.59	62.83	0.07	76.1	76.0
1A4	hydrophobic	high	73	24	23	79.58	1200	6	0.82	167.68	0.19	76.1	76.0
2B1	wetting agent	low	47	16	0	0.00	0	no samples taken		0	0	75.3	68.4
2B2	wetting agent	low	46	15	0	1.36	1200	no samples taken		0	0	75.3	68.4
2B3	wetting agent	medium	82	27	4	17.00	1200	6	1.26	46.54	0.05	75.3	68.4
2B4	wetting agent	high	102	34	14	56.92	1200	6	0.95	120.76	0.13	75.3	68.4
2A1	hydrophobic	low	49	16	5	20.65	1200	6	2.10	89.33	0.10	79.4	56.3
2A2	hydrophobic	low	56	19	6	23.94	1200	6	1.69	89.04	0.10	79.4	56.3
2A3	hydrophobic	medium	91	30	14	50.86	1200	6	2.34	287.33	0.32	79.4	56.3
2A4	hydrophobic	high	116	39	29	102.38	1200	6	1.82	479.82	0.53	79.4	56.3
3B1	wetting agent	low	55	18	2	7.52	1020	4	2.09	32.26	0.04	85.7	44.3
3B2	wetting agent	low	54	18	3	13.21	1020	6	1.13	28.53	0.03	85.7	44.3
3B3	wetting agent	medium	90	30	12	55.27	1020	6	1.35	149.20	0.17	85.7	44.3
3B4	wetting agent	high	148	49	31	115.99	1020	6	2.06	578.67	0.64	85.7	44.3
3A1	hydrophobic	low	56	19	5	24.07	1020	6	0.56	24.53	0.03	73.8	59.8
3A2	hydrophobic	low	58	19	5	26.60	1020	6	0.34	16.27	0.02	73.8	59.8
3A3	hydrophobic	medium	95	32	14	65.41	1020	6	0.37	45.68	0.05	73.8	59.8
3A4	hydrophobic	high	151	50	26	111.75	1020	6	0.52	120.44	0.13	73.8	59.8

Table 5.3. Summary of Results from Plot Experiments (runs standardised to 20 minutes)
Part 2: May 1996 - approximately 28 months after fire.

5.3 Evaluation of Erosion Plot Data and Statistical Analysis

The data was analysed in two stages. Firstly an exploratory Analysis of Variance (ANOVA) following the structure dictated by the experimental design (see Table 5.3) was used. This was used to identify possible effects of experimental treatments. This analysis was exploratory as the experimental design used successive experiments conducted on each plot. Statistically, this approach results in *repeated measures* which necessitates caution in the interpretation of the analysis. Therefore, the statistical significance of the effects at the lower level of the ANOVA (for rain intensity treatment) had to be interpreted with caution.

The effect of the repeated measures were taken into account by the second stage of the analysis. This was achieved by considering slope rather than mean values. This means that the slope of the regression line between response and rain intensity was derived for each plot and used for the analysis. In the case of ln sediment yield this provides a measure of % change in sediment yield per unit change in rain intensity.

The structure of the ANOVA is summarised in Table 5.4 below for ln [sediment yield]. The procedure was the same for other variates.

Table 5.4. Structure used for the Analysis of Variance for ln [sediment yield]

Source of variation	d.f. (m.v)
block stratum	2
block.year stratum	
time	1
Residual	2
block.year.treatment stratum	
hydrophobic	1
time.hydrophobic	1
Residual	4
block.year.treatment.intensity stratum	
rainlevel	2
time.rainlevel	2
hydrophobic.rainlevel	2
time.hydrophobic.rainlevel	2
Residual	27 (1)
Total	46 (1)

The results of the statistical analysis are presented in summary as graphs with accompanying descriptions below. The cut-off P value used for determining statistical significance in this analysis was 0.005 or better. The P values are generally not included here because the interpretation of results used the combination of statistical results from the exploratory analysis and the slope analysis. To evaluate the results and obtain a single P value would require sophisticated statistical modelling which was not used here.

The runoff data is present in graphical form below. For initial assessment, the raw data was plotted both according to time-treatment (Figure 5.2A and Figure 5.3A), ie. a comparison between 4 months and 28 months after the fire, and water repellence / wetting agent -treatment (Figure 5.2B and Figure 5.3B), ie. the comparison between the natural surfaces (called *hydrophobic* series in the graphs) and the surfaces treated with the wetting agent (called *wetting agent*). The labelling of hydrophobic and wetting agent was used for ease of formatting and to avoid confusion. No significant outliers were detected in the scatter plots so all data points were retained.

The graphs (Figures 5.2A and 5.2B) are presented as depth of runoff collected versus depth of rainfall applied, while Figures 5.3A and 5.3B are depicted as peak runoff rate attained versus average rainfall intensity applied. These graphs were generated to identify apparent trends in the data for evaluating the hypotheses that the fire had affected infiltration and runoff generation (Section 1.3 and Section 4.1).

5.3.1 The Effect of Time since Fire on Runoff

Figure 5.2A suggests that the depth of runoff is related to the amount of rainfall applied. As expected, the runoff appears to increase in a linear fashion with an increase in the amount of applied rainfall. Initial inspection of Figures 5.2A and 5.3A shows that there is no suggestion of a difference between the data collected 4 months after fire (May 1994) and 28 months after fire (May 1996) as can be seen in the overlap of the symbols depicting each series.

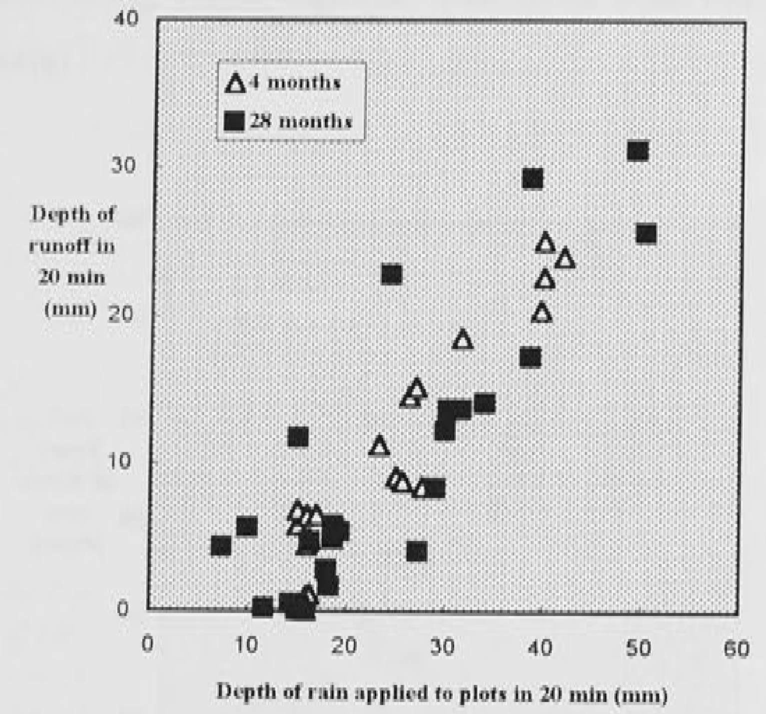


Figure 5.2A. Raw data scatter plot showing the results of total runoff collected as a function of total rainfall applied according to time-treatment for all plots (hydrophobic & wetting agent).

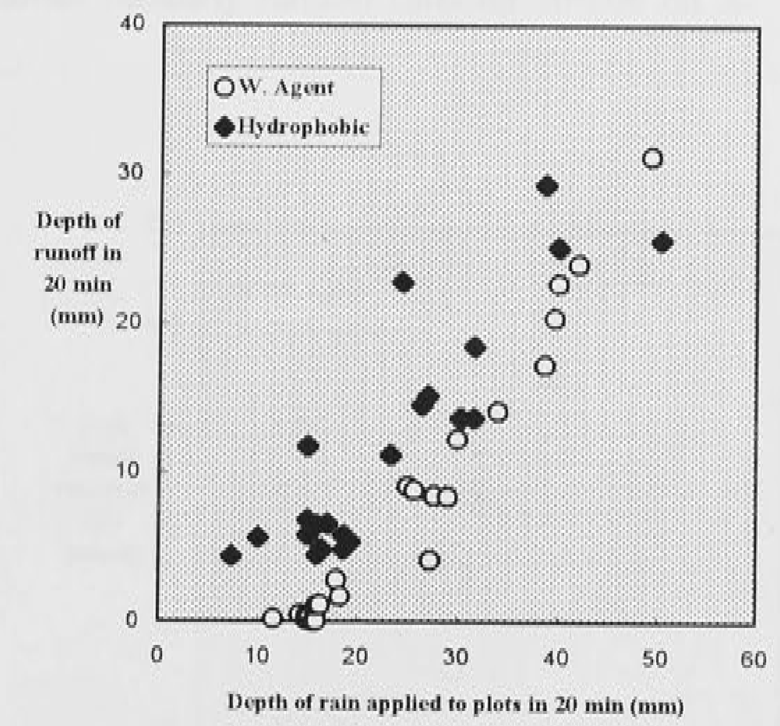


Figure 5.2B. Raw data scatter plot showing the results of total runoff collected as a function of total rainfall applied according to hydrophobic / wetting agent treatment for all plots(4 & 28 months).

5.3.2 The Effect of Water Repellence on Runoff

Figure 5.2B shows the data points labelled as hydrophobic or wetting agent -treated. This apparently results in a separation between the observations for each treatment. The wetting agent treated plots appear to yield less runoff than the hydrophobic plots. However there was no evidence of a difference in response, ie. the rate of increase of runoff depth with applied rain was similar for both treatments.

Figure 5.3A and Figure 5.3B plot peak runoff rate attained in 20 minutes against average rainfall intensity and confirm that there is a linear relationship between peak runoff rate attained in 20 minutes and applied rainfall intensity. The graphs show that as rainfall intensity increases, peak runoff rate also increases.

Figure 5.3A indicates that the response in peak runoff rate to rainfall intensity did not differ between 4 months and 28 months after the fire. This behaviour reflects the observations made in Figure 5.2A.

Similar to Figure 5.2B, Figure 5.3B indicates that the wetting agent resulted in lower peak runoff rate than was measured from the hydrophobic plots for the range of intensities tested. However, there appeared to be a difference in response between the two treatments, ie. at high rainfall intensities, peak runoff for the two treatments was similar while at low rates there was greater separation. This can be observed by the values with an intercept of approximately 150 on X-axis being closer together than those observed at a lower intensity rainfall (around 50-100 on X-axis).

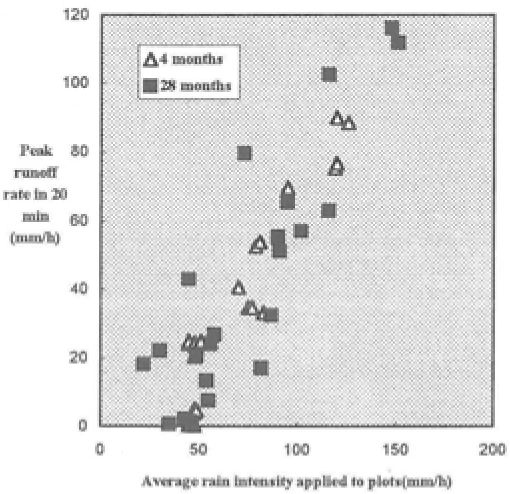


Figure 5.3A. Peak runoff attained vs simulated average rainfall intensity for all experiments with time since fire identified for all plots (hydrophobic & wetting agent).

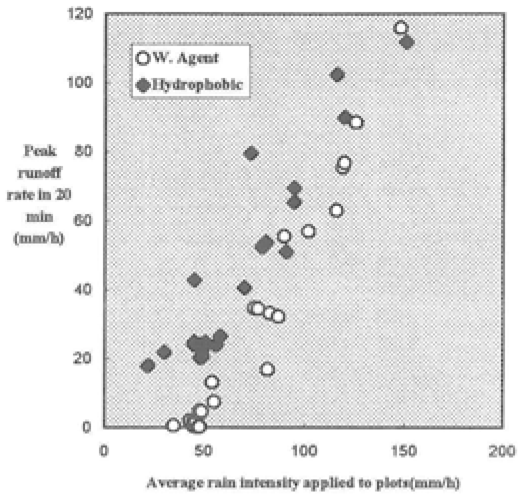


Figure 5.3B. Peak runoff attained vs simulated average rainfall intensity for all experiments with wetting agent treatment identified for all plots (4 & 28 months).

5.3.3 The Effect of Soil Cover on Runoff

Cover was found to range from 44% to 86% (see Table 5.3). The mean value for projected cover is 65% and for contact cover is 55%. Change in cover over time is tested using an ANOVA of cover in below.

The hypotheses developed in Section 4.1 consider cover to be one of the key variables in the regeneration process, that is runoff response over time was expected to be affected by increasing cover level. Figures 5.1A and 5.2A, which compare runoff vs rain for the time-treatment, give no evidence of a relationship between runoff response for the plots tested 4 months after the fire and their corresponding pairs tested 28 months after the fire. Since there was no apparent effect of time-treatment, it is assumed that the increase in cover between May 1994 and May 1996 would not affect runoff rate as proposed in Hypothesis 3.

5.3.4 Statistical Analysis of Runoff Effects

The analysis showed that there is a significant relationship between measured runoff and simulated rainfall applied to the erosion plots. This was the case for both peak runoff attained and

Table 5.5. Sample ANOVA tables for peak runoff

Source of Variation	s.s.	m.s.	v.r.	cov. ef.	F pr.
block stratum	104463	52232	1.66		
block.year stratum					
time	7622	7622	0.24		0.671
Residual	62816	31408	2.94		
block.year.treatment stratum					
hydrophobic	259765	259765	24.28		0.008*
time.hydrophobic	4811	4811	0.45		0.539
Residual	42793	10698	2.08		
block.year.treatment.intensity stratum					
rainlevel	3296975	1648487	320.97		<.001**
time.rainlevel	9723	4863	0.95		0.400
hydrophobic.rainlevel	16051	8025	1.56		0.228
time.hydrophobic.rainlevel	19015	9508	1.85		0.176
Residual	138670	5123			
Total	3810355				
ANOVA adjusted for covariate - Covariate %Projected Cover					
Block stratum					
Covariate	19465	19465	1.53		0.433
Residual	12738	12738	1.83	1.26	
Block.year stratum					
time	1019	1019	0.15	0.13	0.767
Covariate	3924	3924	0.56		0.590
Residual	6954	6954	1.49	0.78	
Block.year.treatment stratum					
hydrophobic	40813	40813	8.73	0.92	0.060
time.hydrophobic	3328	3328	0.71	0.96	0.461
Covariate	1323	11323	0.28		0.632
Residual	14032	4677		0.82	
ANOVA adjusted for covariate - Covariate %Projected Cover					
Block stratum					
Covariate	29746	29746	12.11		0.178
Residual	2456	2456	6.87	6.56	
Block.year stratum					
time	16147	16147	45.20	0.37	0.094
Covariate	10520	10520	29.45		0.166
Residual	357	357	0.12	15.22	
Block.year.treatment stratum					
hydrophobic	50868	50868	16.44	0.90	0.027
time.hydrophobic	8808	8808	2.85	0.80	0.190
Covariate	6073	6073	1.96		0.256
Residual	9282	3094		1.24	

Notes on tables:
*Significant relationship.
**This result also indicates significant relationship but needed additional consideration in interpreting the level of confidence because of the *repeated measure* effect discussed in Section 5.3. The ANOVA of slope in this case did not result in a reduction of confidence level.

depth of runoff collected. Figure 5.4 illustrated this relationship using average rainfall intensity applied plotted against peak runoff attained in 20 minutes. Table 5.5 provides a sample summary of the results of the ANOVA for peak runoff. The relationship between depth of rainfall applied and depth of runoff is similar (and also significant) and therefore not shown here.

Comparing time treatments showed that there was no significant difference (at the 95% Confidence level) between the runoff produced from 4 month and 28 month -post-fire plots for the rainfall intensities applied. Soil cover also had no significant relationship with runoff generation. The data was therefore combined for both years and all cover levels.

The hydrophobic / wetting agent treatments had a significant effect on runoff. Figure 5.5 illustrates the difference between the mean responses on peak runoff for wetting agent treated and hydrophobic soil.

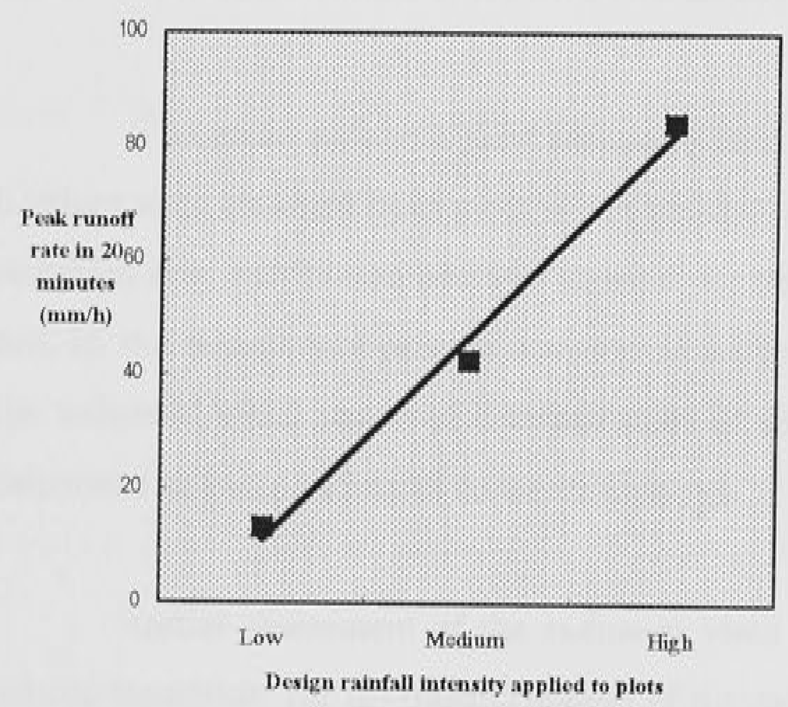


Figure 5.4. The effect of rainfall intensity applied to the erosion plots on runoff generation - peak runoff attained within 20 min.

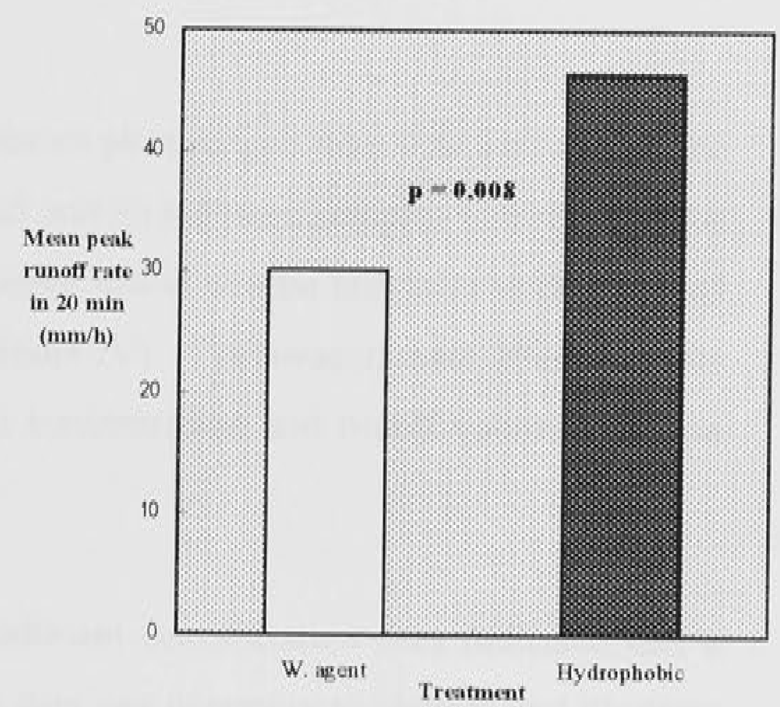


Figure 5.5. The effect of wetting agent / hydrophobic treatment on peak runoff rate attained in 20 min.

The wetting agent / hydrophobic treatment also affected the time-to-peak runoff data, that is the rate at which runoff generation increased and reached its peak during the experiments. The data was skewed however and an effect of the 20 minute limit is likely, ie. the cut-off of 20 minutes meant that runoff curves which were still increasing were clustered at the 20 minute mark. Figure 5.6 illustrates the difference in time-to-peak runoff rate between the wetting agent treated soil and the hydrophobic soil. The probability value shown on the graph denotes the likelihood that the slope of the two equations are the same, that is that the relationship is different between the wetting agent / hydrophobic treatments.

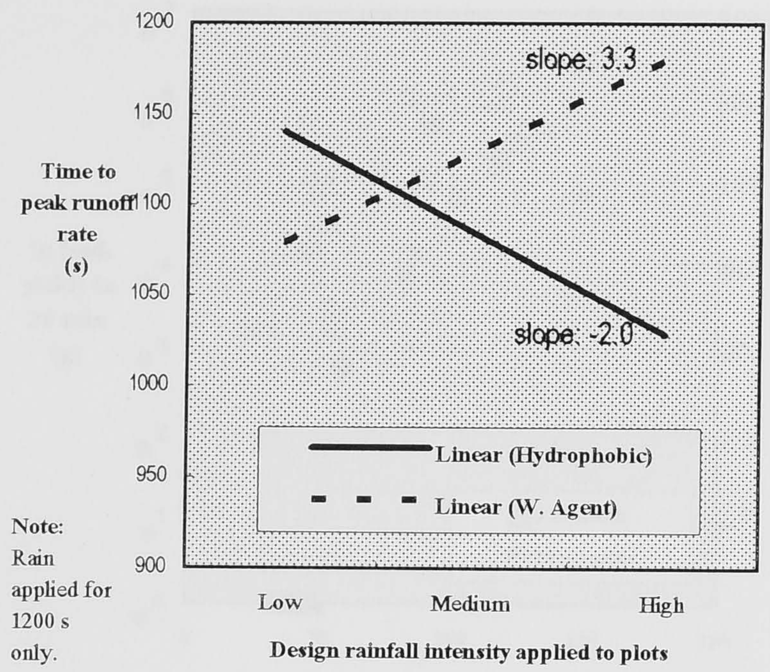


Figure 5.6.
The effect of wetting agent / hydrophobic treatment on time-to-peak runoff rate for the range of intensities applied.

5.3.5 The Effect of Time since Fire on Soil Erosion

The mean sediment yield measured from the erosion plots ranged from 0 to 0.43 tha^{-1}. The 0 values were obtained from plots which yielded no runoff and no sediment samples were taken. The sediment size distribution analysis showed that the sediment was of similar character to the original soil, ie. the detachment process was non-selective (Appendix IV). The measurement of erosion rate (ie. sediment yield) involved determination of sediment concentration and runoff volume and was calculated as mean sediment concentration (gL^{-1}).

Initial assessment of the sediment yield and sediment concentration data indicated that a natural logarithm (or ln) transformation of the sediment data was necessary to identify and illustrate the relationship between rainfall and erosion response for each treatment. The figures and analysis presented here focuses on sediment yield as this data represents a combination of runoff and sediment concentration data.

Figures 5.7A and 5.7B illustrate the overall effect of rainfall intensity on the ln transform of sediment yield. The graphs indicate that as the mean rainfall intensity increases, the ln [sediment yield] increases also in a linear trend. This means that sediment yield appears to be a power function of rainfall intensity. Figure 5.7A shows the comparison between 4 months and 28 months post-fire plots. It is not obvious from this plot whether the two categories are significantly different although the 28 month data series appears to have overall lower values than the 4 month series.

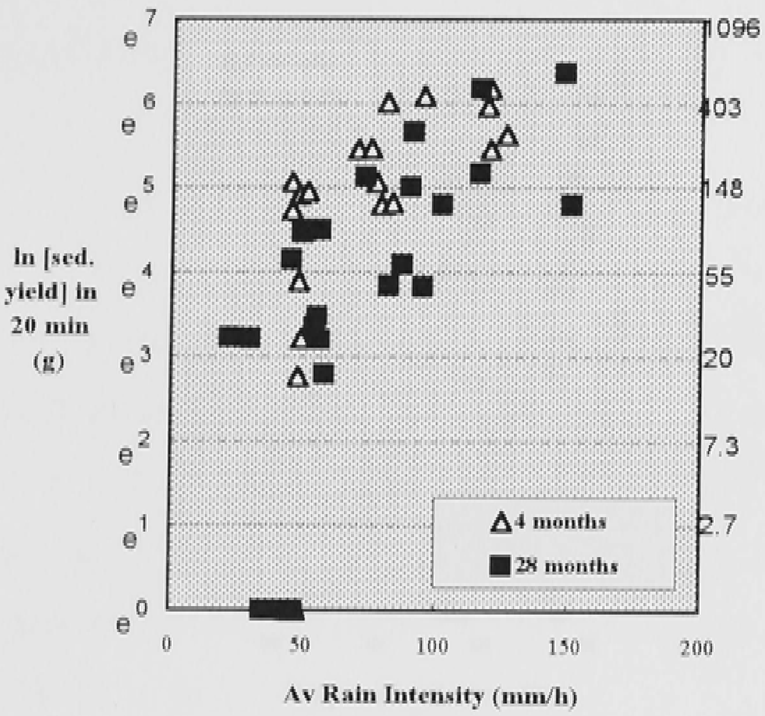


Figure 5.7A. Scatter plot showing the results of ln[sediment yield] versus simulated average rainfall intensity according to time treatment for all plots (hydrophobic & wetting agent).

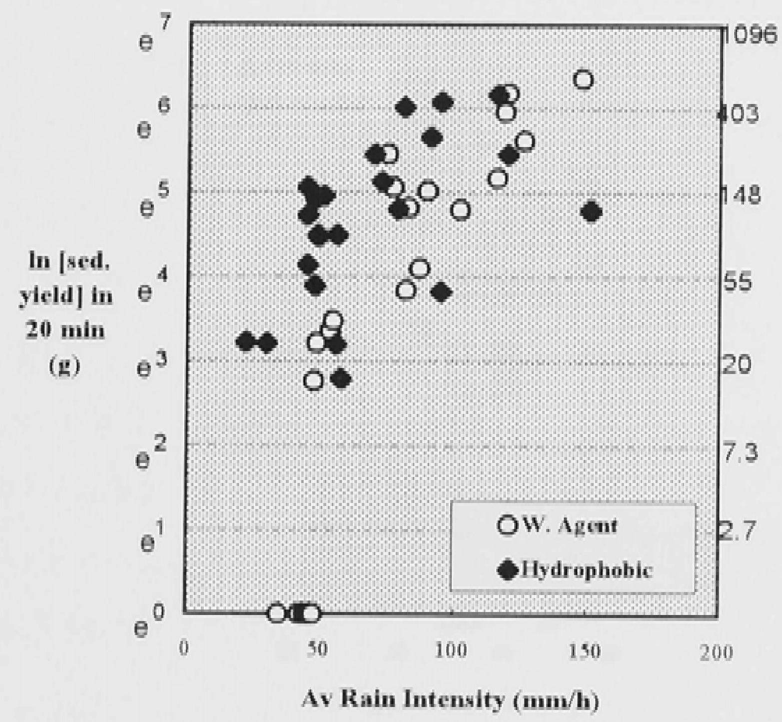


Figure 5.7B. Scatter plot showing the results of ln[sediment yield] versus simulated average rainfall intensity according to hydrophobic / wetting agent treatment for all plots (4 & 28 months).

Note: The Y-axis of these graphs use a natural log scale. The corresponding values are therefore given on the right border of the graph for reference.

5.3.6 The Effect of Water Repellence on Soil Erosion

Figure 5.7B shows the comparison between the hydrophobic plots and the plots treated with a wetting agent. Similarly to Figure 5.7A there is overlap between the data. Even though there is some overlap of the data, there appears to be a difference in response between the two treatments, ie. the hydrophobic series appears to be higher in value overall as well as being more separated from the other treatment at the lower average rain intensities than it is at the higher intensities.

5.3.7 The Effect of Cover on Soil Erosion

Soil cover was plotted against ln [sediment yield] to examine whether cover reduced the level of erosion in these experiments. The data was plotted according to time treatment and graphed separately for projected cover (Figure 5.8A) and contact cover (Figure 5.8B).

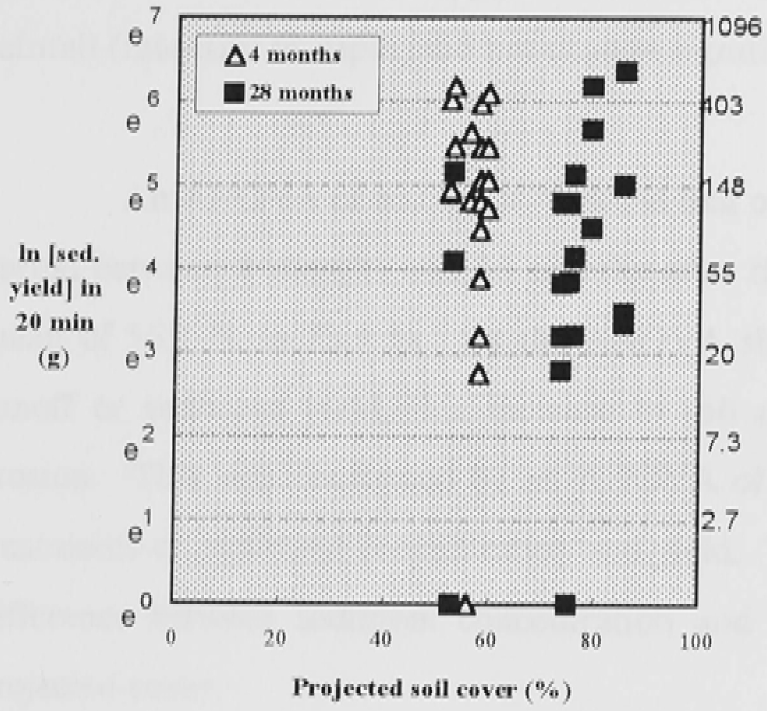


Figure 5.8A. Scatter plot showing the results of ln[sediment yield] versus projected soil cover according to time treatment.

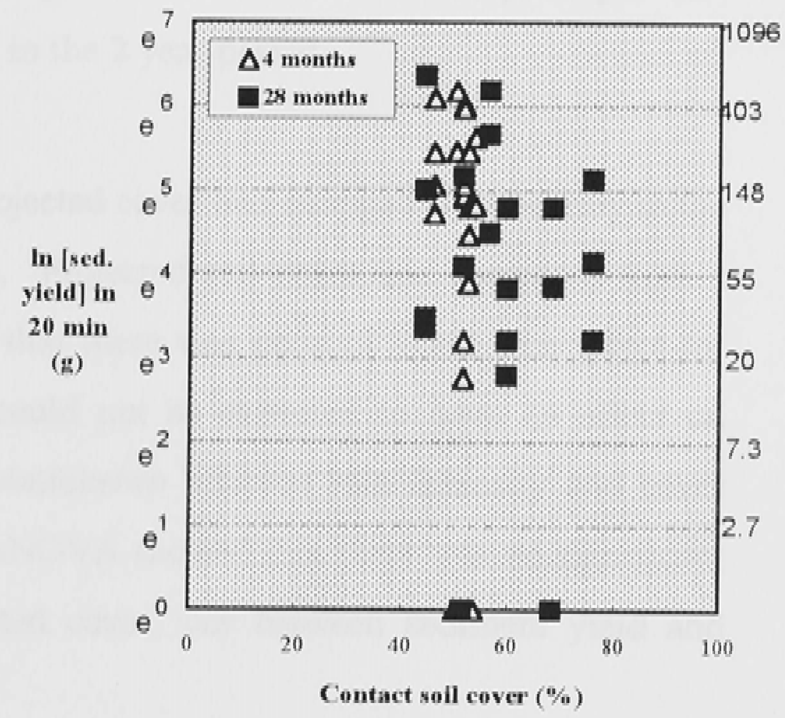


Figure 5.8B. Scatter plot showing the results of ln[sediment yield] versus contact soil cover according to time treatment.

Figure 5.8A suggests that there is no relationship between the level of projected soil cover and sediment yield. This graph shows that projected cover apparently varies between 4 months and 28 months after fire as can be observed by the clustering of symbols for each categories. The values of percentage projected cover appear higher for the 28 month data series. There is no evidence that the level of projected cover has affected sediment yield as the scatter of each category along the Y-axis suggests.

Figure 5.8B shows a similar result for the effect of contact cover on erosion as Figure 5.8A does for projected cover. The mean level of contact cover for the 28 month after fire plots appears to be higher than for the 4 month after fire category. The difference in level of contact cover between the time treatments appear less distinct than that of projected cover due to a greater spread of the 28 month series. Any effect of either category on ln [sediment yield] is again not apparent.

5.3.8 Statistical Analysis of Erosion Effects

The Analysis of Variance confirmed that there was a significant effect of rainfall intensity on sediment yield. Investigation of the time treatment data indicated that this relationship remained the same in the two year period covered by the study as no significant difference in response was found between the 4 month and 28 month categories. This is illustrated in Figure 5.9 which shows that the slope of the line of best fit for each category is not significantly different. While the relationship appears to have remained the same, this graph suggests that the average sediment yield per unit rainfall has decreased slightly from 4 months to 28 months. This is indicated by the line of best fit for the 28 month data series being below that of the 4 month category. However, the

ANOVA showed that this apparent decrease was not significant, ie. the sediment yield per unit rainfall (intensity or depth) did not change significantly in the 2 year period.

An ANOVA of soil cover revealed that only projected cover had changed significantly in the period between 4 months and 28 months after the fire. Projected soil cover had increased from a mean of 56.1 % to 73.9 %. As the ANOVA showed that there was no significant year effect for runoff or sediment yield, this increase in soil cover could not be expected to have an effect on erosion. This was confirmed by an ANOVA of the relationship between rain intensity and cover treatments on sediment concentration and yield. This ANOVA showed that there was no significant difference between sediment concentration and projected cover, nor between sediment yield and projected cover.

A slope analysis (Section 5.3) using projected cover as a covariate was used to test whether projected cover would account for the apparent but non-significant reduction in sediment yield between 4 months and 28 months after fire. No significant effect could be detected, which means that considering the change in cover did not improve the relationship nor account for the apparent variation in sediment yield.

The ANOVA showed that the wetting agent / hydrophobic treatment had a significant effect on erosion response (at the 95% C.L.). Figure 5.10 illustrates the effect of wetting agent treatment and hydrophobicity on sediment yield. The hydrophobic plots yield more sediment at the low intensities applied than the plots treated with the wetting agent but yield approximately the same for the high intensities.

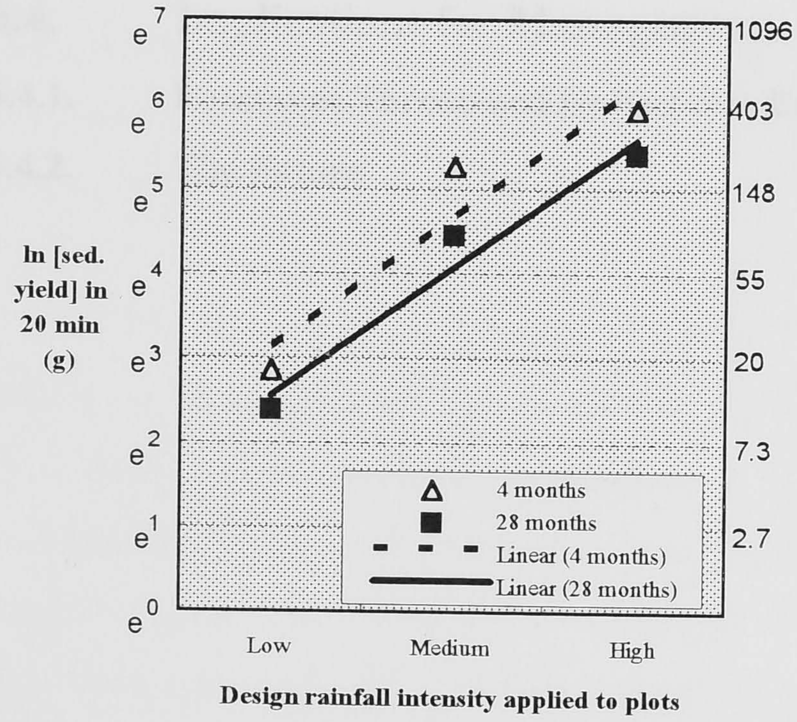


Figure 5.9. The effect of time treatment on sediment yield.

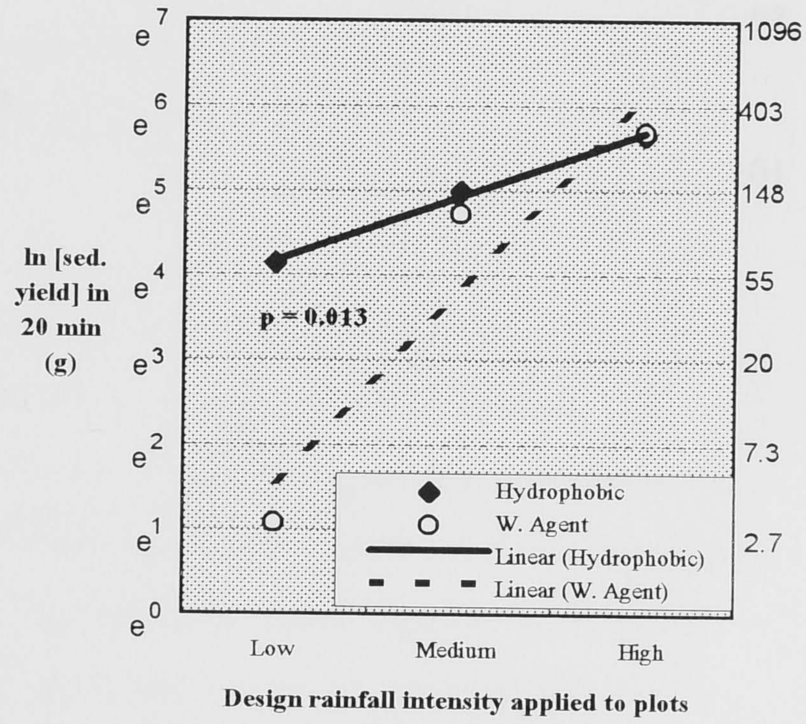


Figure 5.10. The effect of wetting agent / hydrophobic treatment on sediment yield.

Chapter 6

Discussion

6. Discussion

In this chapter the results of the experimental results, described in Chapter 5, are reviewed. The results are discussed in consideration of the limitations imposed by the experimental methodology and the observations made in Chapter 3. The hypotheses given in Sections 1.3 and 4.1 are examined using the findings of the literature review (Chapter 2), the observations reported in the study site section (Chapter 3 and the results of the experiments (Chapter 5). The results of the experimental part of this study are then compared those reported by other researchers (Sections 2.5 and 2.6). Finally, the implications for management of runoff and erosion following fire are discussed on the basis of the findings of this study.

6.1 Summary of Results of the Erosion Experiments

The data described in Chapter 5 and the results of the analysis of experimental data provided in Section 5.3 indicate that the level of runoff and erosion in this fire affected environment is directly related to rainfall intensity. Water repellence is a significant factor in the relationship between runoff and rainfall by limiting the infiltration of rain and increasing runoff. The severity of water repellence as measured directly and deduced from the rainfall simulation experiments did not change significantly between 4 months and 28 months following the fire.

The regeneration of vegetation and associated processes such as litterfall in the 2 years between the field experiments resulted in an increase in soil cover. The 2 years of recovery, including the associated changes in projected soil cover, did not significantly affect the generation of overland flow nor the rate of erosion at the plot level, although there may have been changes at the catchment level.

The magnitude and intensity of simulated rainfall applied ranged from below a 1 in 1 year ARI storm event (22 mmh^{-1} for 20 min) to that approaching a 100 year storm (151 mmh^{-1} for 20 min). Mean percentage runoff ranged from 4 % on plots treated with wetting agent and subjected to low intensity rainfall to 68 % for plots in their natural hydrophobic state subjected to high intensity rainfall (Figure 6.1). This figure also indicates that the effect of water repellence on runoff generation compared with a plot treated with a wetting agent was higher at low rainfall intensity than at high rainfall intensity.

Sediment concentration was found to be highly variable and was not significantly correlated with either cover or rainfall intensity. Sediment yield was found to be a power function of rainfall applied and correlated to rainfall in the same manner as runoff which indicates that erosion is linked to runoff generation. Figure 6.2 summarises the trends in soil loss for the different treatments applied; rainfall intensity, water repellence and recovery time.

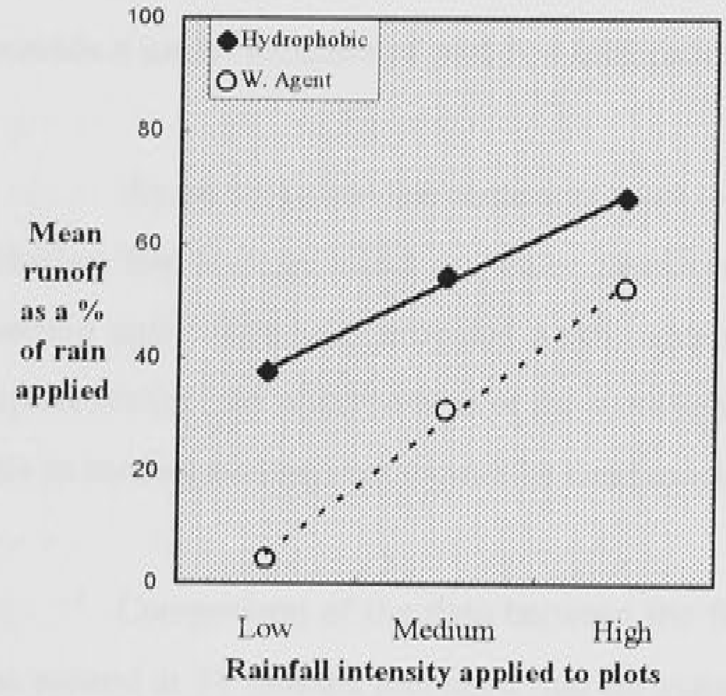


Figure 6.1. Comparison of the efficiency in rain-to-runoff conversion between hydrophobic soil and wetting agent treatment.

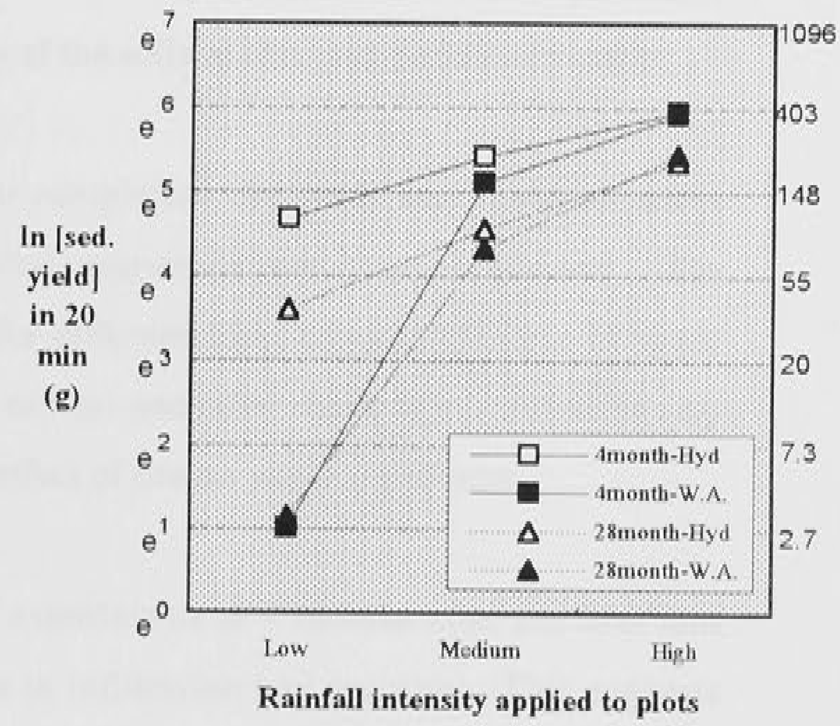


Figure 6.2. Summary of the effect of treatments on sediment yield. Wetting agent and hydrophobic treatments are clearly distinct while the apparent reduction in sediment yield with time was found to be non-significant.

6.2 The Effect of Fire on Runoff

The reports presented in the literature review indicate that fire reduces infiltration and increases runoff volume and rate by a number of different mechanisms. These mechanisms include: (i) inducing or enhancing water repellence in the combustion process, and (ii) the removal of soil cover leading to surface sealing by raindrop impact and the reduction in surface roughness, and the reduction of both interception of rainfall (canopy storage) and depression storage. Additional sealing of the soil surface by clogging with ash has been reported also (Section 2.4.2). Each of these will be discussed in turn.

6.2.1 Water Repellence

This study has shown that water repellence has a major effect on runoff generation in this environment. The effect is more pronounced during rainfall events of low intensity. At higher rainfall intensities, infiltration capacity or soil saturated hydraulic conductivity are expected to become limiting for non-hydrophobic soils which explains the gradual merging of infiltration / runoff curves once rainfall rate approaches overall soil hydraulic conductivity. This means that at very high rainfall intensities, the rainfall vs runoff plots for hydrophobic and wetting agent treated soils are both expected to be parallel to the 1:1 line. The lines would be offset by the value of the soil saturated hydraulic conductivity. Since it was impractical to measure hydraulic conductivity using other techniques, such as a disc permeameter, due to the water repellence the erosion experiments provide a useful measure of post-fire infiltration capacity of the soils in this post-fire environment.

As no unburned site measures were available for comparison this study was unable to assess whether fire had an effect on water repellence and what magnitude any changes attained. The wetting agent treatment provided a reference measure for differentiating between changes in water repellence (or 'the effectiveness of the wetting agent') over time and other changes in infiltration (eg. due to surface sealing) but cannot be used to isolate any effect of fire on water repellence.

Comparison of the data between the first set of experiments at 4 months after the fires and the second at 28 months indicated that no major changes in infiltration had occurred. This suggests that any decay of hydrophobic substances due to wetting and biological activity as indicated by other researchers (Leitch *et al.*, 1983) had not significantly affected infiltration in this environment. The conditions, especially in the first year following the fires were very dry which may have been a factor as water repellence has been observed to be more persistent under these conditions. Dryness (1976) reported a period of 6 years following fire before water repellence returned to its initial level or was removed completely.

Another possibility is that the level of water repellence as measured by its effect on infiltration, did not change as a result of the fires. The mechanism described by Debano *et al.* (1979) and depicted in Figure 2.5 indicates that for an intense fire, the water repellent layer should be shifted from the surface of the soil to below the surface. This is because the initial, pre-fire hydrophobic layer which has resulted from the coating of soil particles by organic compounds leached from litter and secreted by fungi is removed due to the intense heat (see also Figure 2.4). The hydrophobic layer induced by the fire occurs at a depth of soil which remains cool enough during the fire to allow condensation and thus deposition of organic compounds. Although general reports and our observations indicated that the fires in Royal National Park and particularly at our study site were of very high intensity, the water repellent layer after the fire was observed to be at the surface of the soil (Section 5.1, Chapter 3 and Figure 3.6). This indicates that the soil temperatures reached during the burning were not sufficient to decompose the existing water repellent layer or caused the formation of a layer beginning at the surface of the soil.

For any of these scenarios, the fire would be expected to have an effect simply by drying the soil both by heating during the burning and by increasing soil evaporation due to the loss of the litter mulch. Antecedent soil moisture is important in hydrophobic soil because it determines the level of water repellence for each event (Section 2.4.2, Dekker and Ritsema, 1994) while the overall soil moisture regime has an effect because it is associated with biological activity which may break down hydrophobic substances (Section 2.4.2, Dryness, 1976).

None of these effects were detected in the observations made as part of the study or can be resolved from the experimental data. The data provided by the experiments nevertheless provides useful information of the infiltration capacity and runoff generation for a range of rainfall events at a plot level in this environment.

The results also indicated that water repellence shortened the time to peak runoff (Figure 5.7). Figure 5.7 illustrates that on the hydrophobic plots, the time to attain peak runoff rate decreased with increasing rain intensity. The soil treated with wetting agent did not produce significant amounts of runoff within the 20 minutes allocated for each run at low intensities and was still increasing in runoff rate at termination of the medium intensity runs, hence the positive slope on the line. This means that the water repellence results not only in greater volumes of runoff, but also increases the quickflow generation.

Soil cover (projected) increased in the 24 months between the first and second set of experiments due to the regeneration of vegetation and the accumulation of litter. An increase in cover was expected to be associated with a reduction in runoff generation both in volume and rate independent of any effects on the persistence and severity water repellence, (Hypotheses 3, Section 4.1) as reported by other research (eg. Greene *et al.*, 1994a found a decrease in runoff rate with increasing cover). However, this was not observed in this case. A possible explanation for this could be that unlike a forest with several storeys, the heathland vegetation has limited canopy storage which did not significantly effect our measurements. Also, at a small erosion plot level only a very subtle change in runoff retardation could be expected as a result of any apparent changes in surface roughness due to litter accumulation. This effect was not detected in these experiments where runoff generation effects were apparently dominated by the water repellence.

6.2.2 Surface Sealing

As temporal changes in infiltration were not detected in the course of this study, changes in infiltration associated with the protection of the soil from surface sealing seem likely to not have occurred or were negligible at this site. This is not unusual as the breakdown of surface seals may take many years (Ditchfield, 1996) and, similar to the breakdown of water repellence, requires biological activity of the soil which was probably quite low in this soil due to the drought conditions. The breakdown of surface seals in soils with a higher clay content can also be associated with shrink-swell behaviour and the development of cracks in the soil surface. Soils low in clay content may develop different crusts (sieving crusts - Valentin and Bresson, 1992) which do not degenerate in this manner and can therefore be more persistent.

The clogging of pores by ash has been reported to contribute to the sealing process also (Debano *et al.*, 1979) but would require either micromorphological investigation of the surface seals or experiments with ash applied to unburned surfaces not subjected to raindrop impact (to separate the sealing process). Valzano *et al.* (1996) used a micromorphological study to test whether clogging of pores by ash could explain the reduction in infiltration they measured after stubble burning as no water repellence had been detected and infiltration was measured by permeameter. The results of this investigation proved to be inconclusive however.

6.3 The Effect of Fire on Erosion

The effect of fire on soil loss in this environment appears to be closely liked with the generation of runoff. The poor relationship between rainfall intensity and sediment concentration indicates an erosion environment which is detachment limited, ie. the efficiency of the erosion processes depends on the detachment of soil from the original surface not the transport to the bottom of the erosion plot (see also Section 2.1.1). This is also reflected by the apparent lack of sensitivity of sediment yield with respect to runoff. Sediment yield in a transport limited environment should be much more responsive to runoff than the range observed as part of these experiments (Hairsine, 1988). These results are similar to those observed by Greene *et al.* (1994a) who found that sediment concentration was apparently unrelated to rainfall intensity but obtained good relationships between sediment yield and rainfall and sediment yield and runoff.

The 10 % change in soil cover resulting from regeneration of vegetation and accumulation of litter in the two year study period apparently did not change the level of soil loss in this environment. While this is contrary to expectation (Section 4.1), this is not unusual in that the rate of erosion was relatively low to begin with, indicating that the soil surface was resistant to erosion and there was already considerable soil cover. This confirms the observations made (Chapter 3) that the burned but otherwise undisturbed surfaces were quite resistant to erosion.

Sediment concentrations were measured to be quite low (0.5 to 3 gL^{-1}) when compared to the range expected from agricultural soils (generally 30 to 40 gL^{-1}). Figure 2.6 illustrated the effect of soil cover on erosion in an agricultural environment which indicates that erosion increases dramatically once soil cover is less than about 70%. While other factors such as slope also play an important role, the results suggest that the environment represented by the field site is quite resistant to soil erosion, even in a post-fire state. Considering that the range of rainfall intensities applied to the plots were quite high (even the *low* and *medium* intensities were approaching 1in1 and 1in10 year rainfall), this result strongly supports Hypothesis 1 (Section 4.1) which speculated that very high rainfall intensities are required to severely degrade the burned but otherwise undisturbed soil surfaces.

As runoff generation in this environment is linked to water repellence, the effect of water repellence on runoff generation also determines the rate of soil loss, at least at a plot level. Since the majority of the burned but otherwise undisturbed areas are mostly subject to overland flow in the form of sheet flows, this is expected to apply in large parts of the landscape. The role of the litterdams and microterraces (Chapter 3) in keeping overland flows spread relatively evenly over the land surface is therefore seen as an important function considering the efficiency of rain-to-runoff conversion of these severely water repellent soils.

The widespread extent of the water repellence in this environment means that catchment runoff yields are expected to be high and that higher order drainage lines carry increased flows compared with a non-hydrophobic case. The drainage lines therefore have to withstand significant flows. In support of this, Good (1973) reported that the increased runoff following fire was causing deeper incision of existing flow lines. At the hillslope and catchment scale, the increase in soil cover may however begin to have an effect on runoff retardation. The litterdams mentioned above would also have the effect of retarding flows and drawing out the hydrograph.

Our observations indicated that areas which had been subjected to additional disturbance, such as fire breaks and tracks, were subject to rill and gully erosion (Chapter 3). The hypothesis which was developed (Hypothesis 4, Section 4.1) stated that *the interception of sheet flows generated on the fire affected areas by tracks results in catastrophic erosion.* The experiments have shown that the burned but otherwise undisturbed areas are generating efficient in converting rainfall to runoff but are resistant to erosion. This supports the hypothesis in that the experiments showed that sheet flows are generated readily on these slopes but additional disturbance is necessary to trigger catastrophic erosion.

6.4 Implications for Management

Chapters 1 and 3 described the background and development of this study. This study was designed to provide information on runoff and erosion processes following fire. This information could be used to identify appropriate techniques for mitigating any adverse impacts due to fire triggered erosion. There are several limitations imposed by the experimental design and the characteristics of the study site which need to be considered when interpreting the results of the study and extrapolating to other sites and into the future.

For example, Chapter 3 described the dominating influence of the terrace structure on hydrology which is governed by parent rock. The experimental results from the heathland environment, which has relatively uniform, gentle slopes and a considerable depth of soil are therefore likely to be different to the response expected in a forest terrace. The forest terrace association and heathland association can therefore not be compared directly.

Similar to the differences in landscape units in this study, comparisons of studies conducted in other parts of Australia and overseas need to consider site specific factors which may affect the erosion process. The chaparral studies (eg. Booker *et al.*, 1993; Debano *et al.*, 1979) report rill erosion of granite and sandstone derived soil as a result of post-fire runoff events. This response, which has not been observed here, even though the soils were subjected to rainfall approaching 1 in 100 year return events, may be attributed to differences in slope and soil type (Our experiments used a slope of 5 % and 6 metre length). The chaparral when compared to Australian conditions, is a relatively young environment and still subject to tectonic uplift. This means that the soils, which do not have the same extent of profile development, are by comparison unconsolidated and more prone to erosion. Also, most of the areas affected in the Sydney areas are similar in form to the two geomorphic units described, that is the steeper slopes are bench terraces. In the chaparral environment, steep slopes are typically continuous convex to concave slopes which are more prone to rill erosion, ie. the slope length is greater. The areas around Sydney which have long, continuous slopes are gentle slopes such as the coastal heathland which our study showed to be resistant to rill erosion.

6.4.1 Resources Threatened by Post-fire Erosion

When considering what management strategies are most appropriate for a fire affected area, one must first consider what resource is under threat from degradation. In agricultural areas affected by fire, soil erosion is of major importance. Frequently these areas have lost their natural vegetation cover which had evolved with a natural fire regime which was changed as a result of farming and other anthropogenic factors. The vegetation which now covers these areas may not have the capability to regenerate as it does not posses the inherent adaptive traits of the original vegetation. These areas are now mostly used for cropping or grazing. Post-fire seeding with a cover crop to ensure quick re-establishment of soil cover may be appropriate in these areas, although the risk of erosion by seedbed preparation may be elevated after fire because of an increased chance of overland flow.

Much the area burned by the January 1994 fires and areas affected by other bushfires are forests, woodlands and heathlands. These areas are covered by remnant ecosystems which still have adaptive traits to respond to fire. It could be argued that soil erosion, at least as an on-site effect, is not likely to be of any consequence in these areas other than in the way it affects the plant communities in the long term. However, off-site effects such as declining water quality may be important if the areas are used for water harvesting. Damage to infrastructure due to flooding and siltation may also be important. While the management of these effects can be targeted on a fire to fire basis, changes in fire regime due to frequent control burning or arsonists' activities, would be expected to affect both ecology and erosion resistance in the long term.

The potential impact of frequent burning for example is reflected by the catastrophic response observed at the plot level described in Section 2.4.6. which resulted from annual burning. Our study showed that the resistance of the soil to erosion is very important in this post-fire environment. This resistance is, based on our observations, attributed partially to the organic crust (see also Chapter 3, Figure 3.5). The importance of organic crusts or cryptogams in environments where other types of soil cover is well recognised (Section 2.4.3). Greene *et al.* (1990) demonstrated using 7 simulated fires that cryptogamic crusts can be degraded severely by frequent burning which resulted in increased soil loss.

The areal extent of such fires are also an important consideration in identifying management options. Any attempt to treat burned areas on a broadacre scale would quickly become cost prohibitive. Booker *et al.* (1993) assessed post-fire erosion control works costing US$ 5 Million after the Oakland fire and concluded that only where areas were there was additional disturbance was the effort well spent.

Broadacre treatment may also be inappropriate if it is in conflict with the objectives of the management of the area. For example, in Royal National Park and similar conservation areas the risk of weed problems associated with areal seeding with exotic species could threaten the integrity of the ecosystem. In such areas, conservation of the ecosystem is the prime consideration and management options are limited to achieving that goal without creating problems elsewhere.

The risk of adverse impacts from measures applied in an attempt to mitigate erosion further highlights the importance of identification and prioritisation of areas that are actually at risk. For near-natural areas which have evolved with and are therefore adapted to fire, no or minimal intervention appears to be the most appropriate management strategy. This is supported by the reports collated in the literature review (Chapter 2, especially Booker *et al.*, 1993) and our observations described in the study site description (Chapter 3).

The results and discussion of the erosion experiments (Chapter 5 and above) also support the concept that burned but otherwise undisturbed areas are resistant to degradation by erosion. The experiments demonstrated the inherent resistance of this environment to an individual fire event. The study was conducted on an area which had been burned by a severe wildfire. As outlined in Section 2.3.1, severe wildfire is generally accepted as being the most damaging, judged on an event to event basis, because of the intense heat and completeness of the burns. The experiments also used simulated rainfall of an intensity and duration approaching 1 in 100 year rainstorms. The assessment of erosion response in Section 2.4.6 (see Table 2.3) indicates that the combination of wildfire and high intensity rainfall can result in severe erosion. While other factors such as slope are also important, the relatively low rate of erosion observed nevertheless demonstrates the resistance of this environment to erosion in its natural state.

The experiments also showed that in this environment the post-fire runoff coefficients, that is the percentage of rainfall converted to runoff, are high due to water repellence of the soil. Our observations showed that the extensiveness of water repellence and lack of cover resulted in overland flow and sheet erosion. The overland flows were controlled by microtopographical features called litterdams and microterraces which prevent the flows becoming concentrated.

Severe rill and gully erosion was observed along tracks, trails and fire-breaks which was attributed to channelling and concentration of intercepted sheet flows. While these areas are likely to be subject to degradation even without fire, fire appears to exacerbate the problem. As fire is a natural phenomenon in these areas, the design of infrastructure such as roads, tracks and trails should perhaps consider fire regime and post-fire condition when computing the runoff from such areas.

6.4.2 The Future

This study has used the opportunity presented by the January 1994 bushfires to study erosion processes following wildfire. The experiments tested, among other things, the hypothesis that high intensity rainfall is required to cause significant erosion in areas that were disturbed by burning only. This hypothesis was confirmed in that the level of erosion measured in this environment was quite low in comparison to the rate of erosion reported from this type of environment (Section 3.4) and from other areas affected by fire (Section 2.4.6). The percentage increase over background erosion remains to be quantified as there was no measurement possible during the study period. The recovery of vegetation in the 2 years covered by the study had resulted in an increase in soil cover but had not significantly changed the level of runoff and erosion in that 2 year period. This means that post-fire recovery in this environment, at least after 4 months after fire, may be quite slow. While this may be attributed to post-fire weather conditions (drought), it increases the potential for degradation by erosion to occur.

Scott and van Wyk (1992) discussed potential causes of variance in post-fire response. These authors listed the following fire and site characteristics as potentially important:

- season of burn,
- rate and amount of energy released (by the fire),
- geological and soil factors,
- basin morphology,
- vegetation type, and
- climate.

Most of these attributes are inter-related, yet may operate independently and on different levels. For example: vegetation type and pre-fire conditions (climate) determine when fire occurs and at what intensity but post-fire weather (climate), soils and geomorphology determine the hydrological and erosion response.

Prosser and Williams (1997) discuss the importance of rainfall intensity on erosion response. They point out that the impact of fire is essentially to lower the affected landscape's resistance to erosion. The intensity of the fire affects the extent and perseverance (Brunsden and Thornes, 1979) of this lowering effect or increase in *erosion potential*. The *probability* of erosion however also requires the occurrence of an *above-threshold* rain event; ie. rain of sufficient intensity and duration to cause erosion.

Figure 6.3A illustrates a range of scenarios possible for a 3 fires of varying intensity in a landscape. The key points in Figure 6.3A are:

- fires A and B are low to moderate intensity fires while fire C is a high intensity event,
- fires A and B, due to their lower intensity, do not reduce the resistance to erosion to the same extent as Fire C,
- the recovery periods, depicted by the curves between fire event and the 'unburned level' are also shorter and steeper for the milder burns than they are for the intense fire,
- fire B is quicker to recover than Fire A due to the wetter conditions during the recovery period,
- the erosivity of the rainfall events only exceed the unburned level on two occasions, and
- the lowering of the landscape's resistance to erosion results in additional exceedances by rain events of lower erosivity, once during the recovery phase for fire B and twice for fire C.

Figure 6.3B attempts to predict the likely runoff response for these scenarios. The key points depicted by figure 6.3B in conjunction with figure 6.3A are:

- the runoff response to rainfall is greater while the resistance to erosion is lower (ie. in the recovery phase),
- the increase in runoff is greater earlier in the recovery phase than later,
- smaller rainfall events result in a higher percentage runoff per unit rainfall than do larger events due to the effects of water repellence,
- the first rain events in the fire B and fire C recovery phases result in sufficient runoff to erode at 'unburned level' even though the rain erosivity is lower, and
- the response to the rain event with the highest erosivity during the recovery phase for fire C is more severe than the response to the rain event with the same erosivity that occurred after the recovery of fire A and before fire B.

Evaluation of the risk of erosion after fire requires assessment of the degree to which erosion resistance is lowered and the time period for which resistance is lower. Wildfires lower the resistance more and for longer than low intensity fires but tend to occur less frequently. Control burns result in less complete burning and therefore leave the soil surface with a higher runoff threshold, but are more frequent. The high frequency of low intensity fire may result in longer periods of fire affected soil than infrequent wildfire. The window of opportunity for runoff and erosion producing rainfall to occur may therefore be greater with a fire regime of many low intensity burns. The effect of such a regime on ecology and species composition is another factor which needs to be considered, both in terms of how it affects ecosystem integrity and soil erosion due to changes in soil cover and soil-plant-atmosphere interactions.

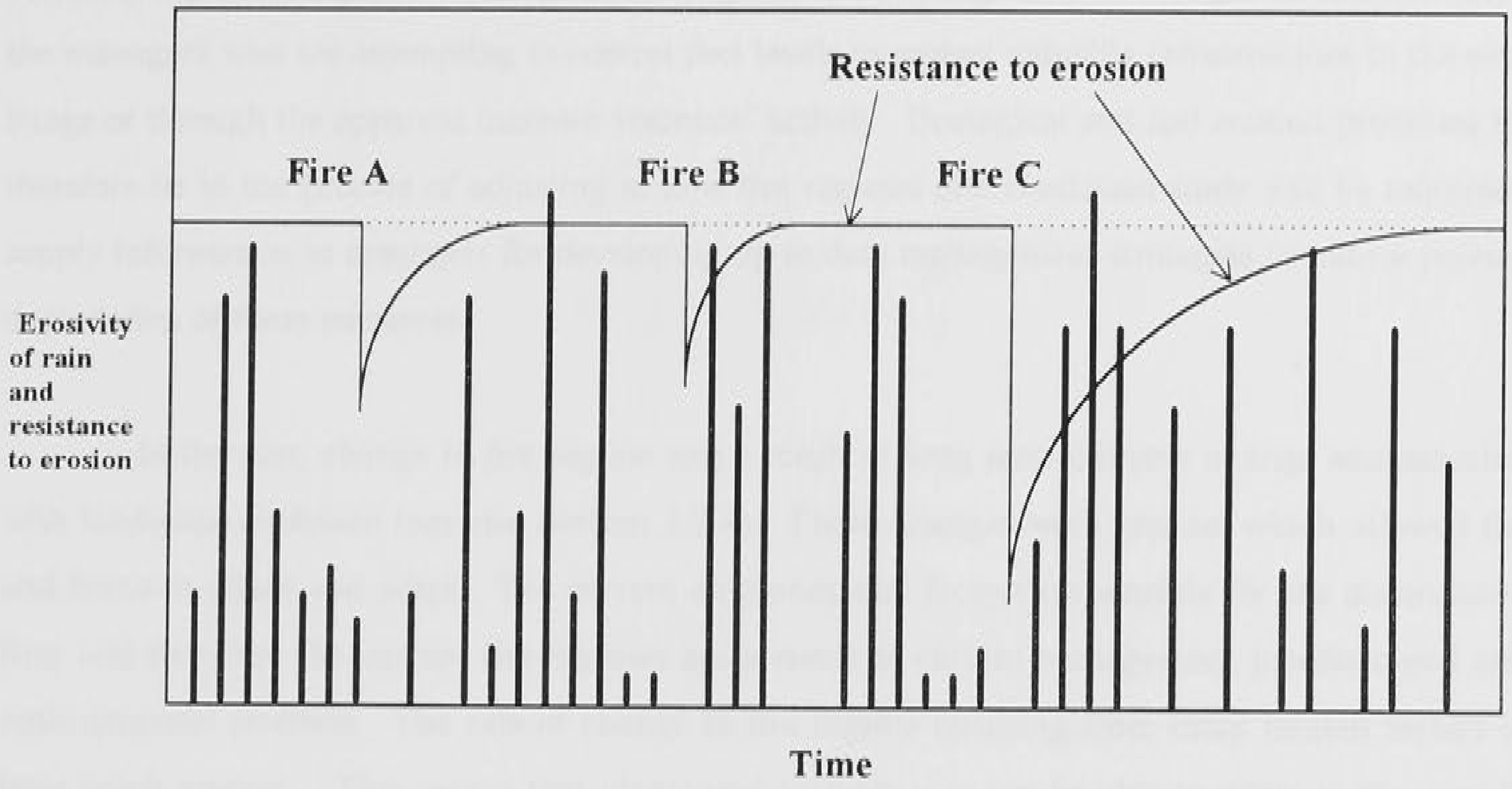


Figure 6.3A. (above) Conceptual model of the effect of fire on erosion potential. The occurrence of erosion depends on the exceedance of the resistance-to-erosion line (or threshold).

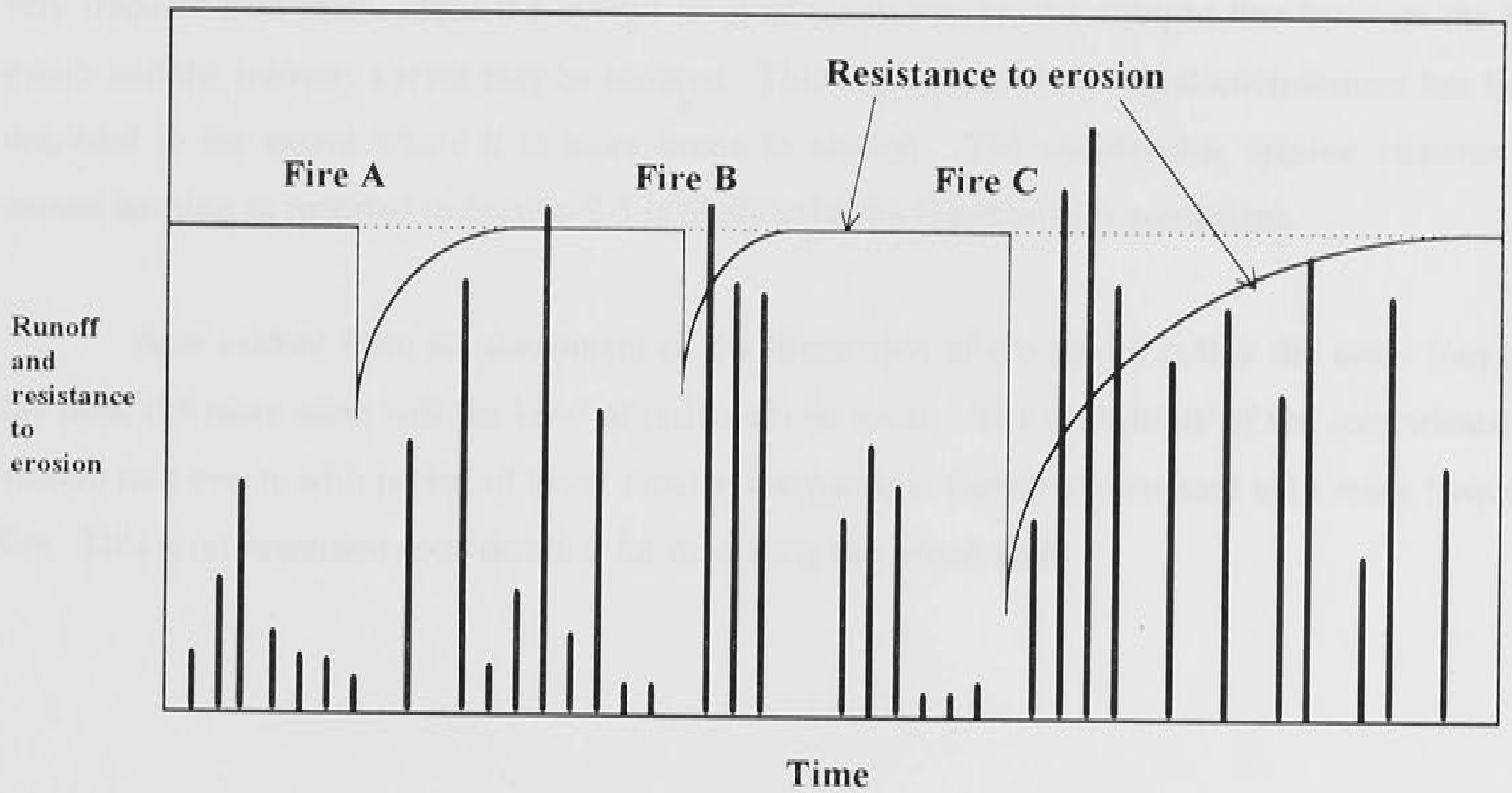


Figure 6.3B. (above) Conceptual model of the runoff and erosion response to fire. The magnitude of runoff and erosion is indicated by the exceedance over the resistance-to erosion line.

Many of the areas affected by fire in the Australian environment have experienced or are currently experiencing such a change in fire regime. This change may be brought on intentionally by the managers who are attempting to control fuel levels to protect valuable infrastructure in the urban fringe or through the apparent increase arsonists' activity. Ecological and soil erosion processes may therefore be in the process of adjusting to new fire regimes and continued study will be required to supply information to managers for developing up to date management strategies to reduce potential degradation of these resources.

In the past, change in fire regime was a result of long term climatic change and associated with landscape evolution (see also Section 2.2.4). These changes were gradual which allowed flora and fauna to adjust and adapt. The current environmental factors responsible for the occurrence of fires and therefore the current fire regimes are a result of current management practices and other anthropogenic artefacts. The rate of change in fire regime resulting from these human factors has been much greater. This means that plants and animals may not be able to adapt to the new fire regime as they have in the past in a more natural system. Added pressures such as the fragmentation of the remnant ecosystems are also of concern.

The conceptual model illustrated above assumes that there is a fairly constant level of resistance to erosion in the environment, which may fluctuate with seasonal variation (not shown on the illustration) but is only lowered significantly by fire. The model also indicates that while the rate of recovery may vary, the level of resistance recovers to reach the original level. It is possible that very frequent fires may reduce the overall level of resistance, ie. the straight line between the fire events and the recovery curves may be lowered. This implies that the natural environment has been degraded to the extent where it is more prone to erosion. The catastrophic erosion response to annual burning as reported in Section 2.5 is likely to be the result of such conditions.

Also evident from an assessment of the illustration of the model is that the more frequent the fires, the more often will the level of resistance be lower. The probability of the coincidence of erosive rain events with period of lower erosion resistance is therefore increased with more frequent fire. This is an important consideration for managing fire prone areas.

Chapter 7

Conclusions

7. Conclusions

Occurrences of bushfires in almost all landscapes of Australia are natural processes. Much effort has been targeted at reducing the impacts of fire on life and property. This effort has been aimed at avoiding the occurrence of fire or controlling its spread. However, fire will continue to be an integral part of the Australian environment.

Managers of areas of remnant vegetation, which are prone to developing wildfires capable of catastrophic impacts on life and property are faced with the dilemma of attempting to conserve ecosystem integrity while being obligated to reduce fire risk. A genuine need for more information on the impacts of fire on landscape processes, including the impact on soil has been identified. This information is needed to help these managers in developing strategies for solving this problem. This study has investigated runoff and soil erosion processes in one ecosystem affected by fire, ie. a slope of coastal heathland in the north-eastern part of Royal National Park. However, further and ongoing study will be required to fill our knowledge gaps and monitor inevitable change brought on by continued development.

7.1 Evaluation of the Hypotheses

This project set out to provide information on runoff and soil erosion in fire affected landscapes. The study focussed on an area within the north-eastern part of Royal National Park and used erosion plot experiments at a site situated on a heathland slope of about 5% slope. The experiments compared a range of treatments; *low*, *medium* and *high* intensity simulated rainfall, a wetting agent vs water repellent comparison and a comparison between soil condition at 4 months and 28 months after intense wildfire.

The results of the experiments indicate that water repellence is a major factor in limiting infiltration of rainfall and the generation of runoff in this environment. The post-fire surfaces yielded high runoff but were subject to limited erosion due to the resistance of the soil surface and the spreading of flow by micro-topographical features in the form of debris dams. There was no indication that the rates of runoff generation and soil erosion had declined between 4 months and 28 months after the fires, despite an increase in projected soil cover.

These results combined with the observations obtained during the course of the study and a review of the literature allow for a partial evaluation of the hypotheses developed (Sections 1.4 and 4.1) and some general conclusion to be drawn.

Hypothesis 1 stated that *the natural, post-fire soil surface is resistant to erosion and incision by raindrop impact and overland flows produced by patterns of average rainfall in this environment and that extreme rainfall events are required to initiate degradation.* The results from the experiments support this hypothesis in that the rate of erosion, ie. up to a maximum rate of soil loss of 0.67 t ha^{-1}, resulting from simulated rainfall approaching events of 1 in 100 year return period was not severe and incision (rill erosion) was not observed on natural, post-fire surfaces. This conclusion is reinforced when the observed rates are compared to those reported in the literature (Section 2.5 and 2.6).

Hypothesis 2 stated that *the generation of sheet flow has been changed by the fire due to the loss of soil cover and reduction in infiltration rate.* As no unburned area was available for comparison, the study had to limit its experimental evaluation to the 2 year period available. The experimental results obtained in this time did not support this hypothesis as no significant change in runoff generation could be detected between 4 months and 28 month after the fire. Soil cover (projected) had increased as a result of vegetation recovery but apparently did not affect runoff or soil erosion processes at the scale of measurement, ie. at a plot level. It is anticipated that the change in soil cover may have an effect on catchment scale runoff and erosion but this was not tested in this study. Water repellence was found to have a significant effect on runoff and soil erosion. It is unknown whether fire had induced or enhanced water repellence in this environment, as reported by other studies, although it is likely from our observations that the soils in this landscapes are naturally water repellent and that the fire merely enhanced this characteristic.

Hypothesis 3 stated that *regeneration of plant cover will reduce the rate of overland flow and soil loss.* Soil cover increased within the duration of the study but was shown to have no significant effect on runoff and erosion processes in this environment at the scale of measurement used by the study.

Hypothesis 4 stated that *the interception by tracks of sheet flows generated on the fire affected areas results in catastrophic erosion.* This hypothesis could only be evaluated by inference as no measurements specifically for that purpose were taken. The results from the plot experiments indicate that the runoff coefficients of the natural post-fire surfaces are high which confirmed earlier observations that sheet flows were extensive in the study area. The channelling of flows was readily observed during natural rain events and on the qualitative evidence, such as fresh deposits of litter, ash and soil, gathered by observation. The deterioration of tracks was severe in many areas although some of the erosion may pre-date this fire.

Hypothesis 5 stated that *the effect of water repellence on infiltration has been altered by the fire. Regeneration of plant cover, accumulation of litter and breakdown of hydrophobic* *substances will reduce the effect of water repellence over time.* As for Hypotheses 2 and 3, these factors could not be validated nor dismissed. Water repellence was measured to have a significant effect on runoff and therefore erosion but did not change during the course of the study, possibly due to the drought conditions prevailing for much of this period.

7.2 Recommendations for Management

From these conclusions, three important recommendations for management can be made.

Firstly, the additional runoff and erosion resulting from the fires appears to be not cause problems in undisturbed areas which should be left to regenerate naturally.

Secondly, the design of tracks and trails, especially with regard to location and drainage, should take the high runoff coefficients into consideration to avoid the concentration of overland flows.

Finally, the undisturbed soil surfaces are partly protected by organic crusts, which have been shown to deteriorate by annual burning. The fire regime of these areas should therefore be monitored. If fuel reduction burning is to be carried out, the effects of a burning program on vegetation and organic crusts must be taken into consideration.

7.3 Limitations of the Study

The nature of this study and therefore the conclusions reached were limited by time and resources. In addition, the interpretation of results was limited due to the lack of an unburned area for comparison. Future studies should attempt to include an unburned control area where possible. The inability to do so in our case was due to the severity of the January 1994 fires which serves as a reminder of how severe and widespread the impact of fire can be in the Australian environment.

The study used a very limited number of samples which restricted the evaluation, especially when attempting to detect what may have been a subtle change in runoff and erosion as a result of cover regeneration.

The drought conditions following the fire may have slowed the regeneration of cover and increased the persistence of water repellence during the time period studied. A rainfall record for the site is not available as our monitoring equipment was repeatedly vandalised. Prosser and Williams (1997) experienced similar drought conditions and pointed out that prolonged drought conditions, with a possible link to Southern Oscillation - El Niño cycles, are not only uncommon in Australia but may well be causal to the occurrence of fire. What may therefore appear to be a limitation due to particular climatic conditions during the time available for study, could be representative for this environment. If this is the case, future studies should, if possible allow more time if they set out to study the recovery process and identify the period of increased risk of degradation following fire.

7.4 Suggested Further Research

As mentioned earlier, there are many gaps in our current knowledge on fire related processes which need to be addressed if we are to improve our knowledge base and management of this important factor in the Australian environment.

This study has identified water repellence as being an important factor in runoff generation and soil erosion. Further study of this phenomenon should consider extent, severity and persistence of water repellence to help evaluate impacts on hydrology and soil erosion. The relationship of water repellence with fire and post-fire soil-plant processes also requires further study.

The effect of a changing fire regime on these environments will require ongoing monitoring and detailed studies. Where burning is part of a management routine, this information will aid in assessing the impacts of this regime on the soil-plant system and developing an appropriate strategy.

The natural resistance to erosion of the soil present in the study site is worthy of further study also. The organic crust in particular appears to be an important component and should be studied for its biological and physical attributes.

A study of the conditions immediately following fire would also help to identify and assess processes associated with ash layers and surface sealing.

Nutrient dynamics and ecological processes have not been a focus of this study but are also regarded as extremely important for their long term impact on soil as well as in their own right when considering our increasing awareness of the value of biodiversity and genetic resources.

Chapter 8

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APPENDIX I

Water Repellence Determination

Results of Field Observations for WDPT (refer to Section 4.2 for Methodology).

2/03/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	0	10	10
50-100	0	0	0	10	10
100-150	0	0	4	6	10
150-200	-	-	-	-	-
200-250	-	-	-	-	-
250+	-	-	-	-	-
Total	0	0	4	26	30

13/07/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	0	40	40
50-100	0	0	3	17	20
100-150	0	0	8	12	20
150-200	0	5	0	0	5
200-250	0	5	0	0	5
250+	2	8	0	0	10
Total	2	18	11	69	100

29/03/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	0	10	10
50-100	0	0	6	4	10
100-150	0	0	7	3	10
150-200	-	-	-	-	-
200-250	-	-	-	-	-
250+	-	-	-	-	-
Total	0	0	13	17	30

27/09/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	7	33	40
50-100	0	0	15	5	20
100-150	2	10	5	3	20
150-200	2	3	0	0	5
200-250	3	2	0	0	5
250+	9	1	0	0	10
Total	16	16	27	41	100

14/05/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	4	36	40
50-100	0	0	3	17	20
100-150	0	0	10	10	20
150-200	0	5	0	0	5
200-250	0	5	0	0	5
250+	10		0	0	10
Total	10	10	17	63	100

11/01/95

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	4	36	40
50-100	0	0	5	15	20
100-150	0	0	4	16	20
150-200	0	5	0	0	5
200-250	0	5	0	0	5
250+	10	0	0	0	10
Total	10	10	13	67	100

21/05/94

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	5	33	38
50-100	0	0	8	16	24
100-150	0	0	9	9	18
150-200	0	5	0	0	5
200-250	3	2	0	0	5
250+	10	0	0	0	10
Total	13	7	22	58	100

2/05/96

depth	non-wr	slightwr	strongwr	severewr	Total
0-50	0	0	9	31	40
50-100	0	0	7	13	20
100-150	0	0	7	13	20
150-200	0	5	0	0	5
200-250	0	5	0	0	5
250+	10	0	0	0	10
Total	10	10	23	57	100

Investigation of Water Repellence Monitoring Data: Change in WDPT over Time

By Date

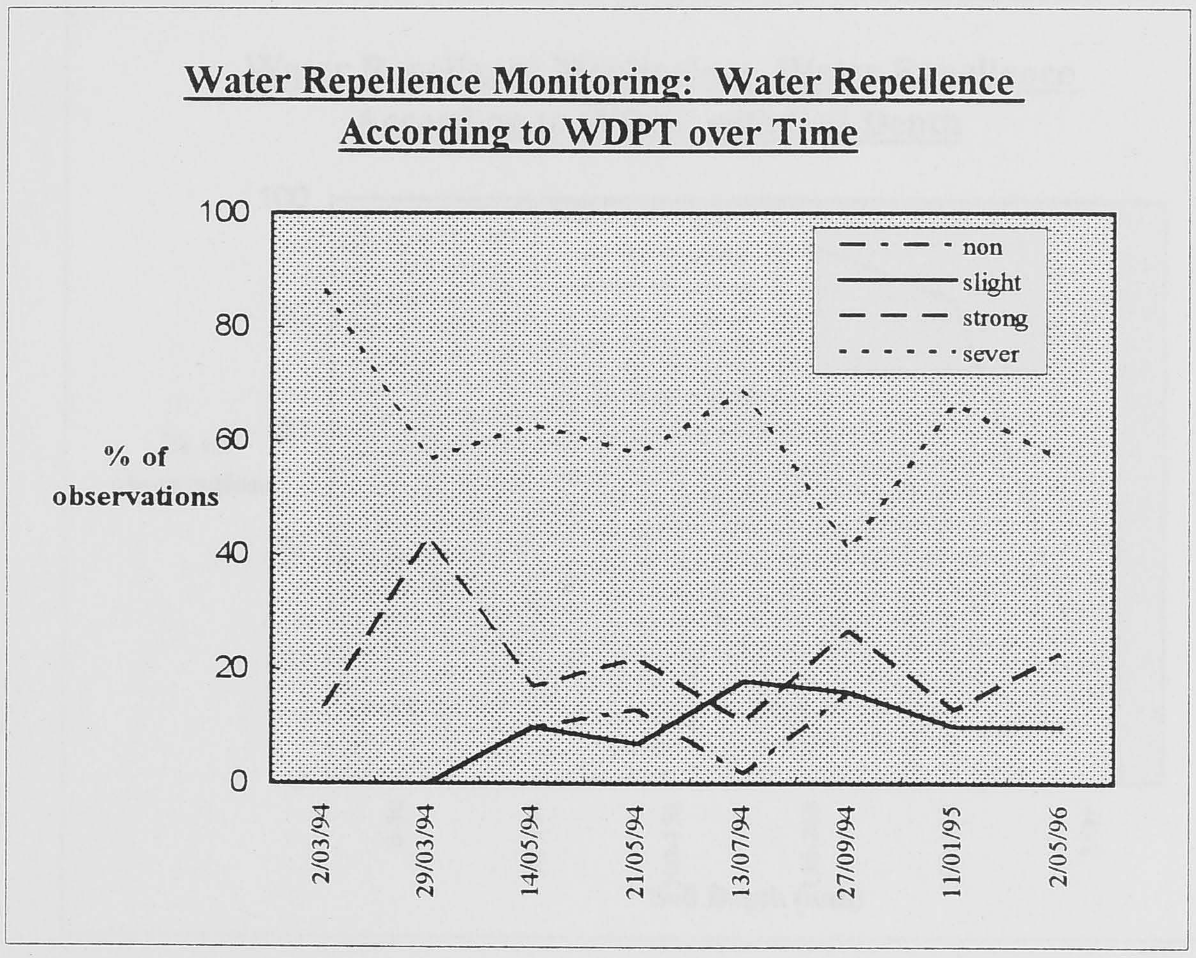
Date	non	slight	strong	sever	total
2/03/94	0	0	4	26	30
29/03/94	0	0	13	17	30
14/05/94	10	10	17	63	100
21/05/94	13	7	22	58	100
13/07/94	2	18	11	69	100
27/09/94	16	16	27	41	100
11/01/95	10	10	13	67	100
2/05/96	10	10	23	57	100
total	61	71	130	398	660

% of observations

Date	non	slight	strong	sever
2/03/94	0	0	13	87
29/03/94	0	0	43	57
14/05/94	10	10	17	63
21/05/94	13	7	22	58
13/07/94	2	18	11	69
27/09/94	16	16	27	41
11/01/95	10	10	13	67
2/05/96	10	10	23	57

STATISTICS

	non	slight	strong	sever
mean	8	9	21	62
stdev	6	7	11	13



Note: First two dates only 30 samples in top 150mm of soil were taken.

Investigation of Water Repellence Monitoring Data: Variation in WDPT with Soil Depth

By Depth

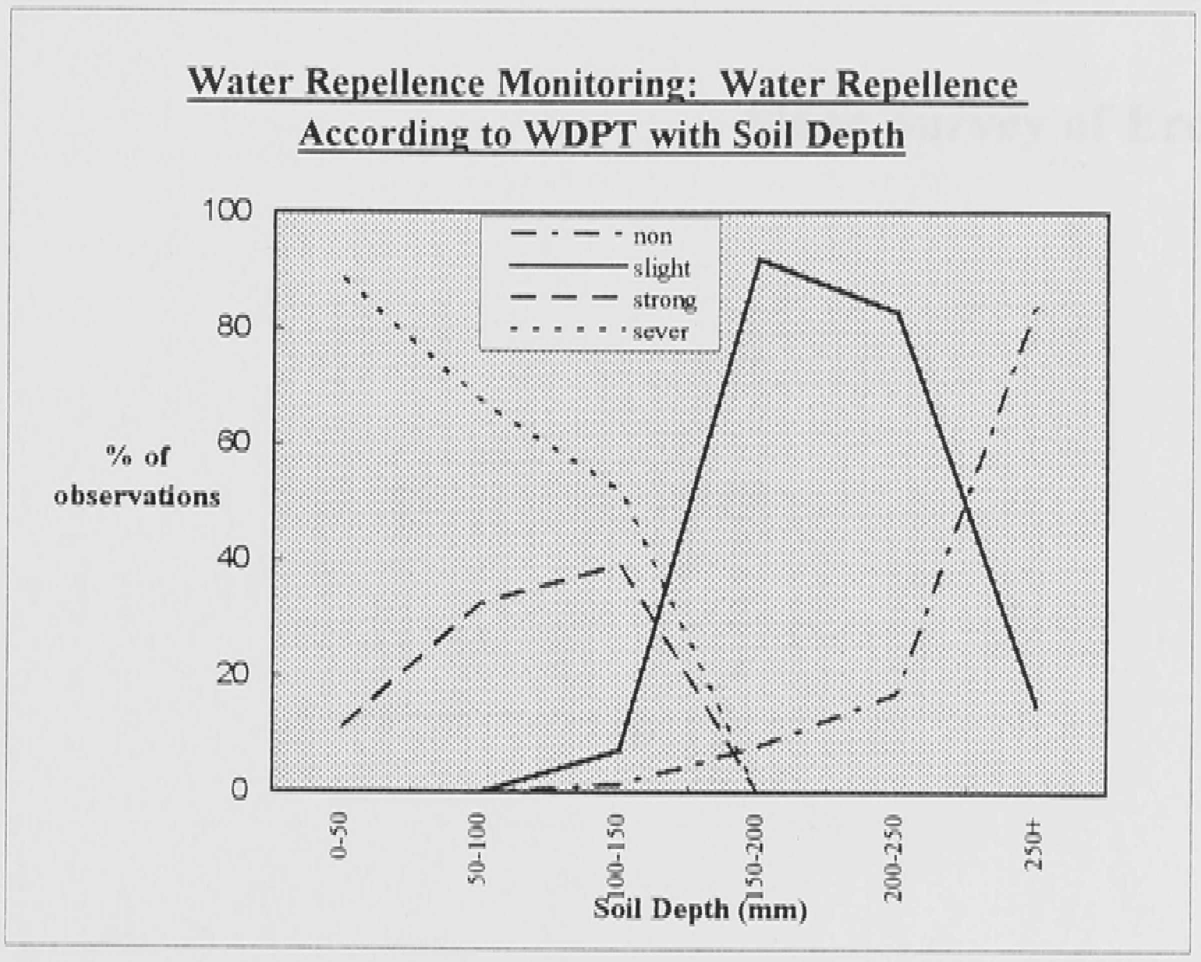
Depth(mm)	non	slight	strong	sever	total
0-50	0	0	29	229	258
50-100	0	0	47	97	144
100-150	2	10	54	72	138
150-200	2	23	0	0	25
200-250	6	29	0	0	35
250+	51	9	0	0	60
total	61	71	130	398	660

% of observations

Depth(mm)	non	slight	strong	sever
0-50	0	0	11	89
50-100	0	0	33	67
100-150	1	7	39	52
150-200	8	92	0	0
200-250	17	83	0	0
250+	85	15	0	0
total	9	11	20	60

STATISTICS

	non	slight	strong	sever
mean	19	33	14	35
stdev	33	43	18	40



Note: First two dates only 30 samples in top 150mm of soil were taken.

APPENDIX II

Slope Survey of Erosion Plots

Plot Survey: Levelling; CZ,HZ. 20/5/94

PLOT 1a (Fieldbook)

6	1.370	1.377	1.397
5	1.428	1.433	1.440
4	1.466	1.457	1.457
3	1.502	1.510	1.505
2	1.535	1.530	1.533
1	1.597	1.615	1.615
0	1.641	1.650	1.665
	0	0.75	1.5

PLOT 1a

	0.00	0.75	1.50
6.0	0.295	0.288	0.268
5.0	0.237	0.232	0.225
4.0	0.199	0.208	0.208
3.0	0.163	0.155	0.160
2.0	0.130	0.135	0.132
1.0	0.068	0.050	0.050
0.0	0.024	0.015	0.000

Recording in Fieldbook

PLOT1b	0.00	0.75	1.50
6.0	1.328	1.328	1.305
5.0	1.360	1.381	1.375
4.0	1.408	1.404	1.404
3.0	1.443	1.450	1.432
2.0	1.480	1.472	1.487
1.0	1.550	1.518	1.527
0.0	1.588	1.585	1.572

PLOT1b

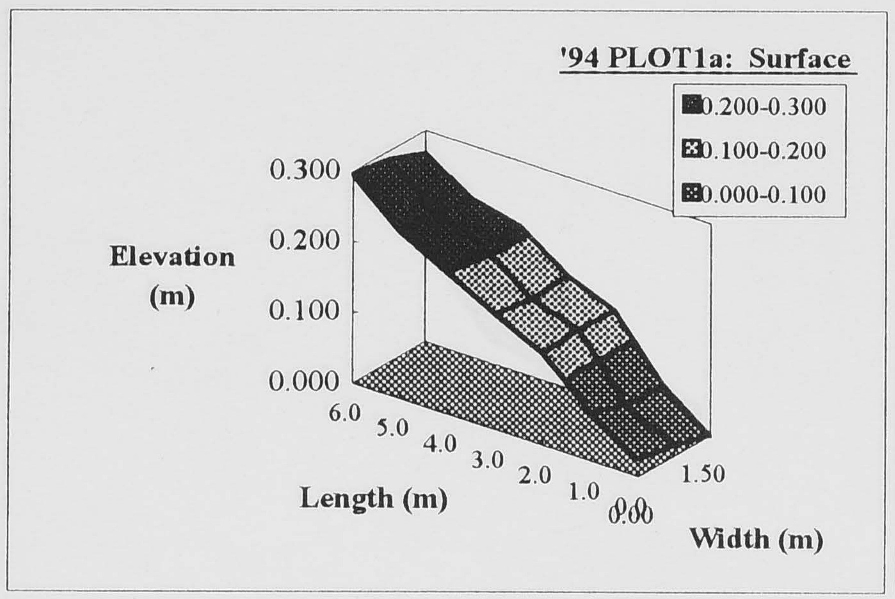
	0.00	0.75	1.50
6.0	0.260	0.260	0.283
5.0	0.228	0.207	0.213
4.0	0.180	0.184	0.184
3.0	0.145	0.138	0.156
2.0	0.108	0.116	0.101
1.0	0.038	0.070	0.061
0.0	0.000	0.003	0.016

Recording in Fieldbook

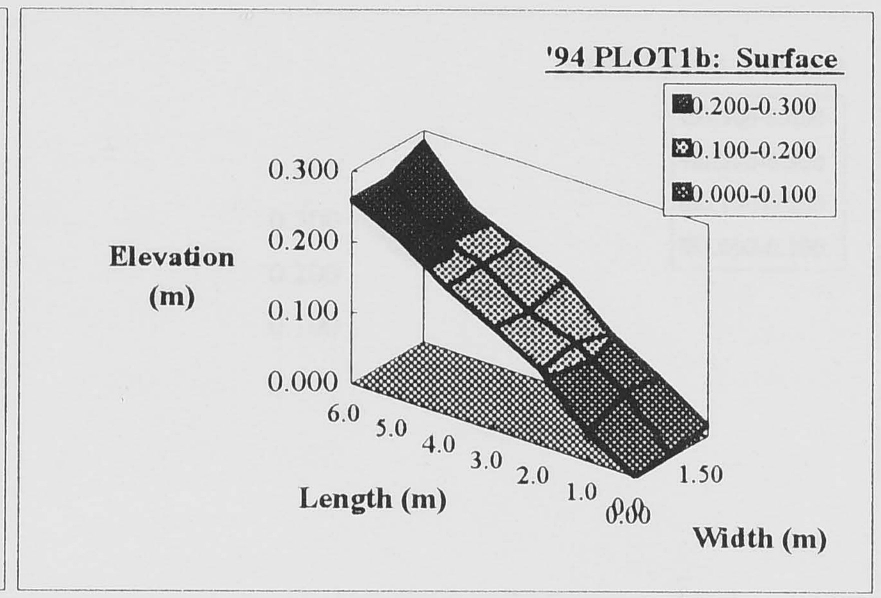
PLOT2a	0.00	0.75	1.50
6.0	1.455	1.460	1.468
5.0	1.481	1.488	1.498
4.0	1.528	1.546	1.531
3.0	1.603	1.613	1.605
2.0	1.662	1.670	1.664
1.0	1.726	1.717	1.715
0.0	1.783	1.762	1.755

PLOT2a

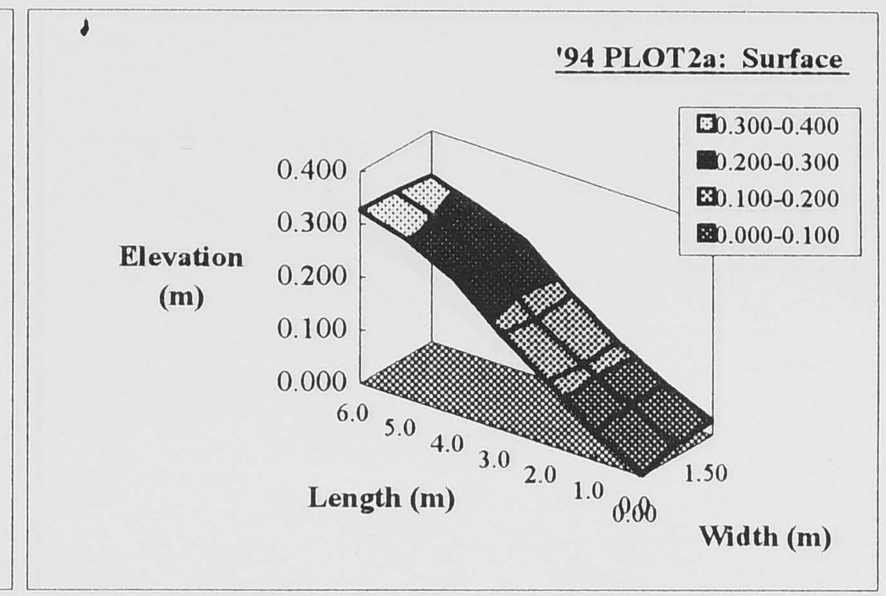
	0.00	0.75	1.50
6.0	0.328	0.323	0.315
5.0	0.302	0.295	0.285
4.0	0.255	0.237	0.252
3.0	0.180	0.170	0.178
2.0	0.121	0.113	0.119
1.0	0.057	0.066	0.068
0.0	0.000	0.021	0.028



Mean slope: 4.9%



Mean slope: 4.7%



Mean slope: 5.5%

Recording in Fieldbook

PLOT2b	0.00	0.75	1.50
6.0	1.087	1.080	1.089
5.0	1.135	1.123	1.135
4.0	1.173	1.171	1.190
3.0	1.247	1.226	1.231
2.0	1.260	1.283	1.263
1.0	1.317	1.318	1.315
0.0	1.370	1.360	1.340

PLOT2b

	0.00	0.75	1.50
6.0	0.283	0.290	0.281
5.0	0.235	0.247	0.235
4.0	0.197	0.199	0.180
3.0	0.123	0.144	0.139
2.0	0.110	0.087	0.107
1.0	0.053	0.052	0.055
0.0	0.000	0.010	0.030

Recording in Fieldbook

PLOT3a	0.00	0.75	1.50
6.0	1.010	1.018	1.010
5.0	1.062	1.056	1.072
4.0	1.089	1.102	1.108
3.0	1.132	1.155	1.159
2.0	1.185	1.204	1.216
1.0	1.171	1.223	1.262
0.0	1.333	1.303	1.314

PLOT3a

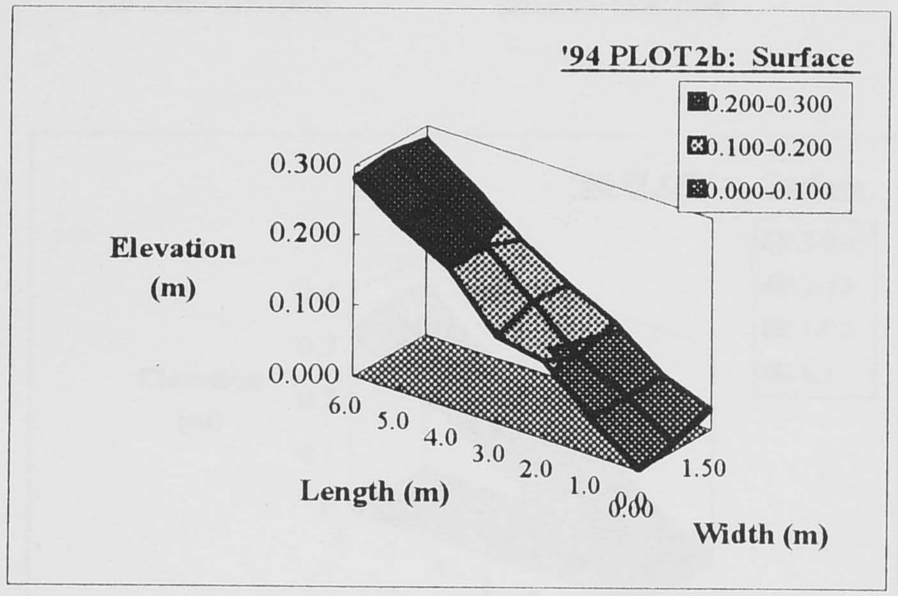
	0.00	0.75	1.50
6.0	0.323	0.315	0.323
5.0	0.271	0.277	0.261
4.0	0.244	0.231	0.225
3.0	0.201	0.178	0.174
2.0	0.148	0.129	0.117
1.0	0.162	0.110	0.071
0.0	0.000	0.030	0.019

Recording in Fieldbook

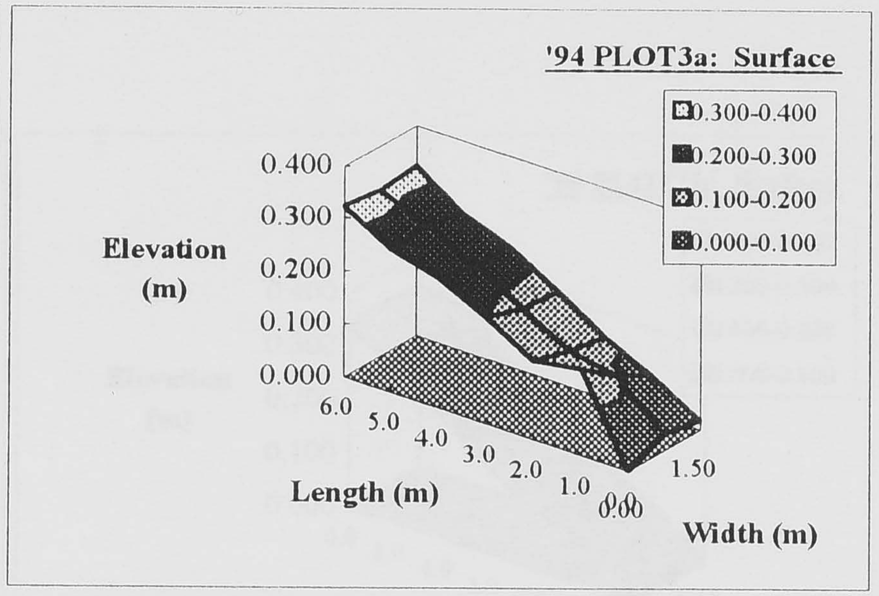
PLOT3b	0.00	0.75	1.50
6.0	1.064	1.063	1.023
5.0	1.090	1.103	1.086
4.0	1.143	1.152	1.141
3.0	1.196	1.193	1.197
2.0	1.233	1.237	1.221
1.0	1.294	1.304	1.287
0.0	1.339	1.342	1.319

PLOT3b

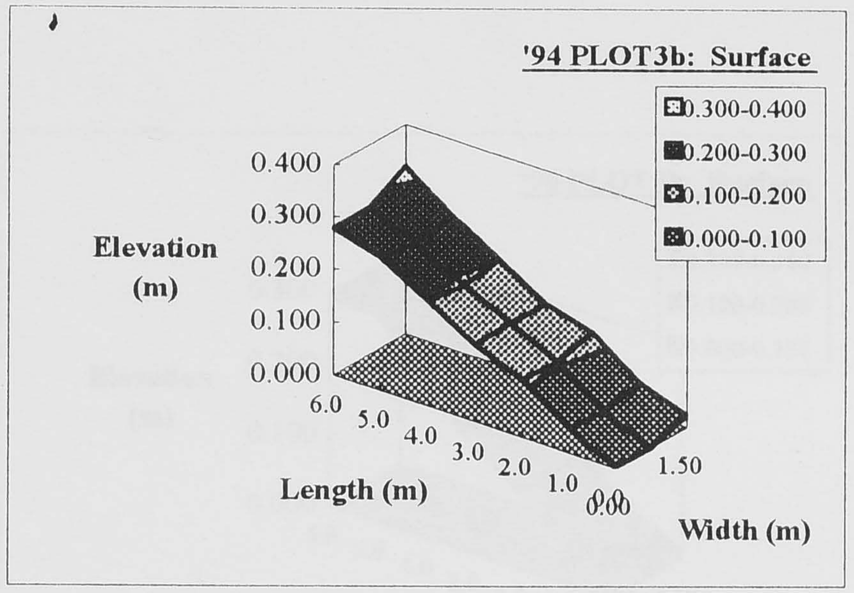
	0.00	0.75	1.50
6.0	0.278	0.279	0.319
5.0	0.252	0.239	0.256
4.0	0.199	0.190	0.201
3.0	0.146	0.149	0.145
2.0	0.109	0.105	0.121
1.0	0.048	0.038	0.055
0.0	0.003	0.000	0.023



Mean slope: 4.8%



Mean slope: 5.4%



Mean slope: 5.3%

t Contour Survey for 1996 FRS Experiments

3/05/96

CZ, NO'S

PLOT 1a (Fieldbook)

	0	0.75	1.5
6	1.59	1.574	1.573
5	1.633	1.638	1.65
4	1.683	1.689	1.713
3	1.739	1.719	1.731
2	1.799	1.776	1.798
1	1.83	1.87	1.856
0	1.912	1.917	1.908
			outflow

(southern most plot)

PLOT 1a

	0	0.75	1.5
6	0.327	0.343	0.344
5	0.284	0.279	0.267
4	0.234	0.228	0.204
3	0.178	0.198	0.186
2	0.118	0.141	0.119
1	0.087	0.047	0.061
0	0.005	0	0.009
			outflow

(southern most plot)

PLOT 1b (Fieldbook)

	0	0.75	1.5
6	1.469	1.464	1.472
5	1.52	1.506	1.493
4	1.581	1.568	1.564
3	1.649	1.631	1.64
2	1.702	1.7	1.697
1	1.721	1.752	1.743
0	1.782	1.809	1.809
			outflow

PLOT 1b

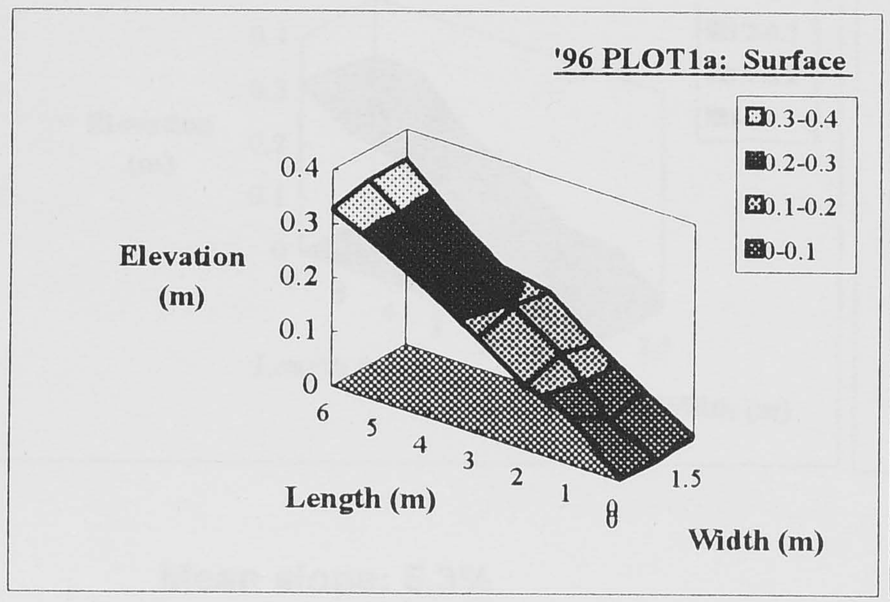
	0.00	0.75	1.50
6.0	0.340	0.345	0.337
5.0	0.289	0.303	0.316
4.0	0.228	0.241	0.245
3.0	0.160	0.178	0.169
2.0	0.107	0.109	0.112
1.0	0.088	0.057	0.066
0.0	0.027	0.000	0.000
			outflow

PLOT 2b (Fieldbook)

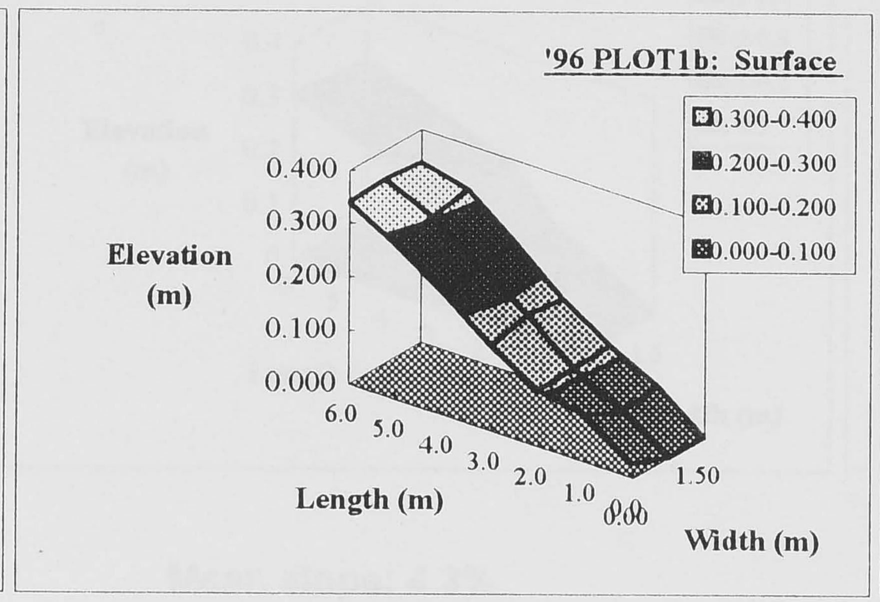
	0	0.75	1.5
6	1.203	1.198	1.208
5	1.203	1.246	1.263
4	1.267	1.289	1.307
3	1.342	1.34	1.349
2	1.38	1.394	1.403
1	1.437	1.437	1.453
0	1.494	1.484	1.485
outflow			

PLOT 2b

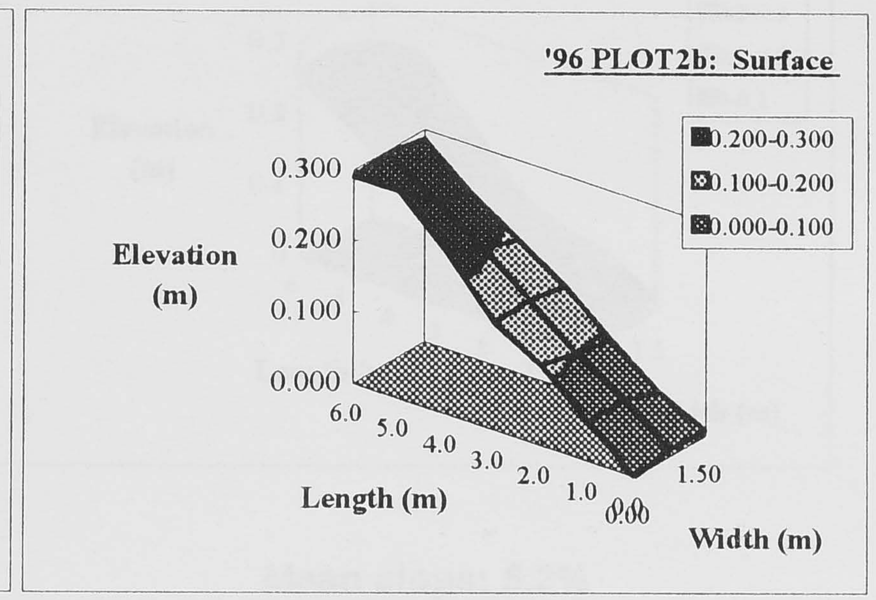
	0.00	0.75	1.50
6.0	0.291	0.296	0.286
5.0	0.291	0.248	0.231
4.0	0.227	0.205	0.187
3.0	0.152	0.154	0.145
2.0	0.114	0.100	0.091
1.0	0.057	0.057	0.041
0.0	0.000	0.010	0.009
outflow			



Mean slope: 5.7%



Mean slope: 5.8%



Mean slope: 4.9%

CZ, NO'S

PLOT 2a (Fieldbook)

	0	0.75	1.5
6	1.622	1.636	1.65
5	1.68	1.66	1.653
4	1.702	1.708	1.743
3	1.76	1.753	1.778
2	1.802	1.82	1.853
1	1.837	1.85	1.86
0	1.924	1.938	1.924

outflow

PLOT 2a

	0	0.75	1.5
6	0.316	0.302	0.288
5	0.258	0.278	0.285
4	0.236	0.23	0.195
3	0.178	0.185	0.16
2	0.136	0.118	0.085
1	0.101	0.088	0.078
0	0.014	0	0.014

outflow

PLOT 3b (Fieldbook)

	0	0.75	1.5
6	1.367	1.38	1.386
5	1.4	1.409	1.415
4	1.441	1.452	1.452
3	1.492	1.494	1.482
2	1.563	1.56	1.581
1	1.607	1.621	1.623
0	1.659	1.67	1.677

outflow

PLOT 3b

	0	0.75	1.5
6	0.31	0.297	0.291
5	0.277	0.268	0.262
4	0.236	0.225	0.225
3	0.185	0.183	0.195
2	0.114	0.117	0.096
1	0.07	0.056	0.054
0	0.018	0.007	0

outflow

PLOT 3a (Fieldbook)

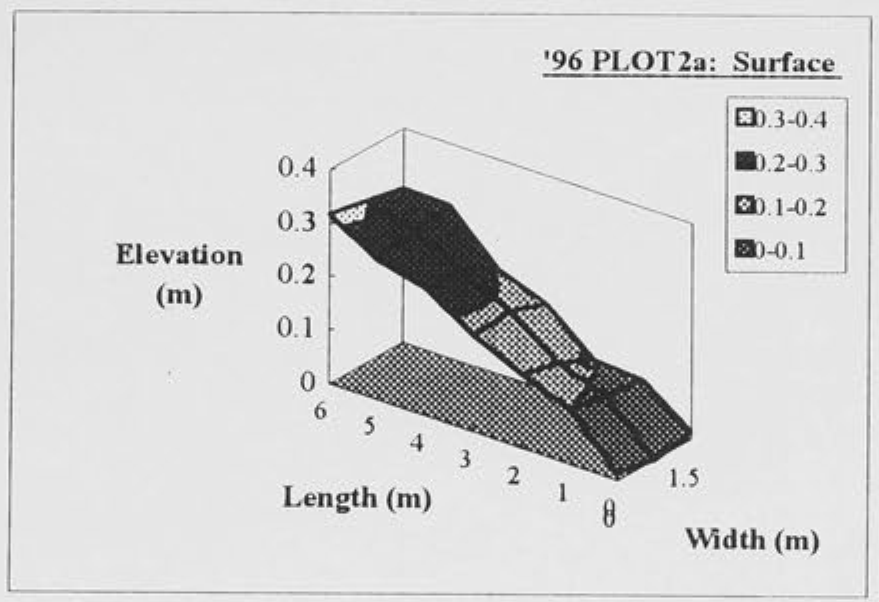
	0	0.75	1.5
6	1.061	1.06	1.077
5	1.111	1.092	1.068
4	1.152	1.125	1.137
3	1.194	1.198	1.213
2	1.238	1.238	1.249
1	1.285	1.26	1.262
0	1.32	1.299	1.301

outflow

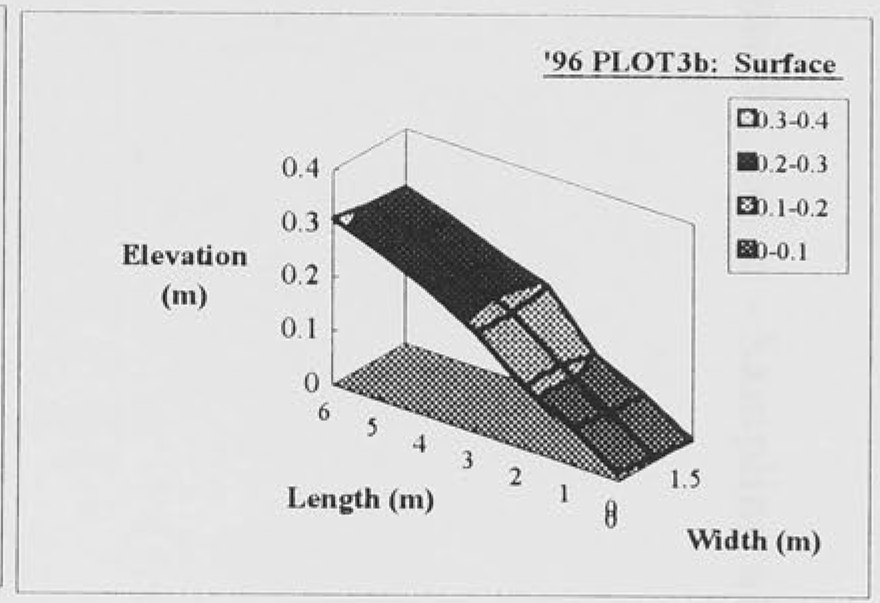
PLOT 3a

	0	0.75	1.5
6	0.259	0.26	0.243
5	0.209	0.228	0.252
4	0.168	0.195	0.183
3	0.126	0.122	0.107
2	0.082	0.082	0.071
1	0.035	0.06	0.058
0	0	0.021	0.019

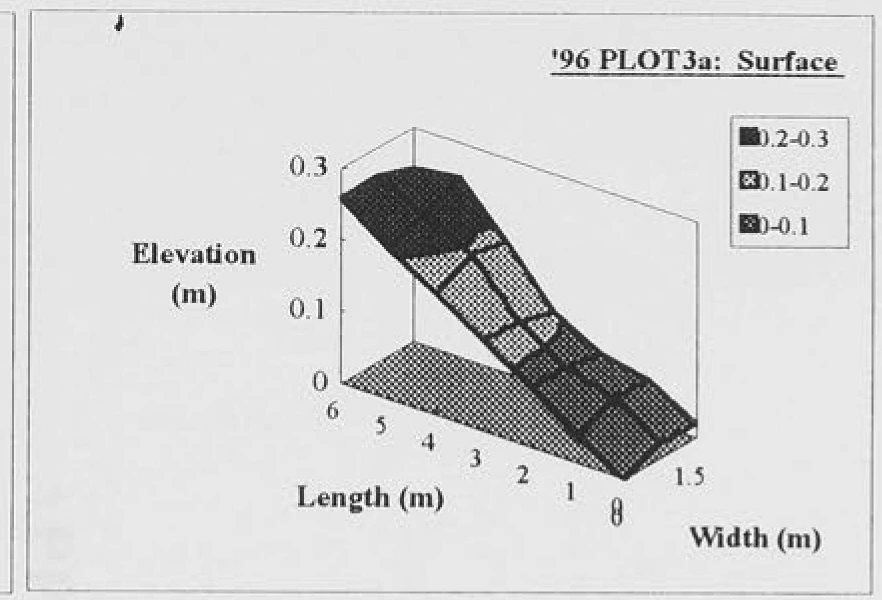
outflow



Mean slope: 5.3%



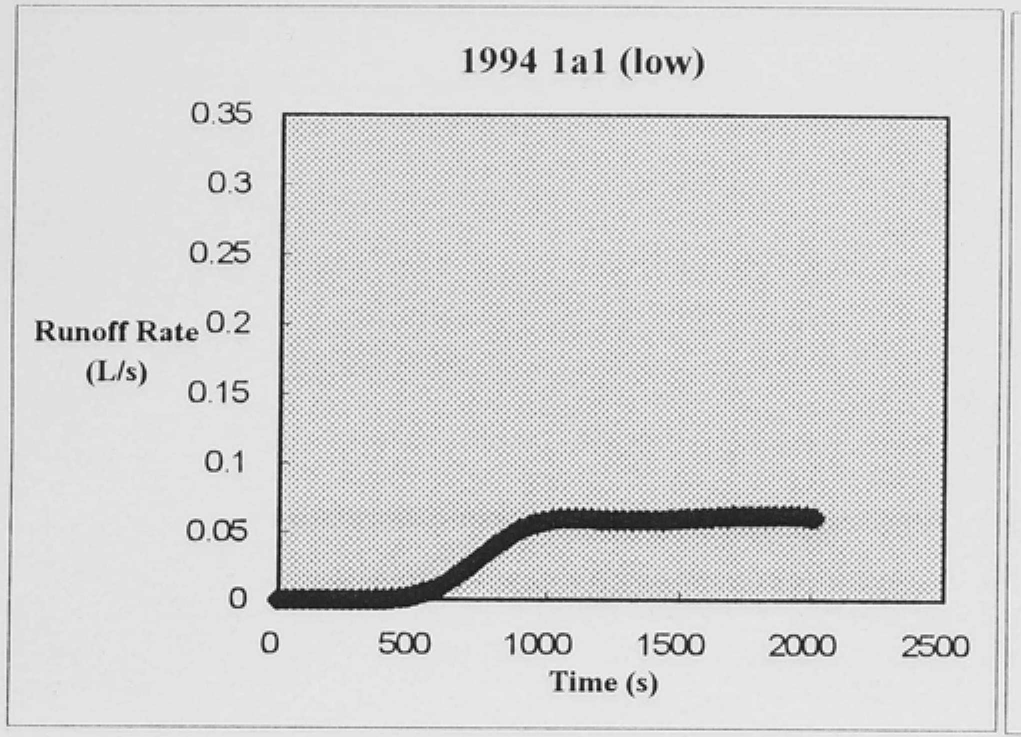
Mean slope: 4.3%

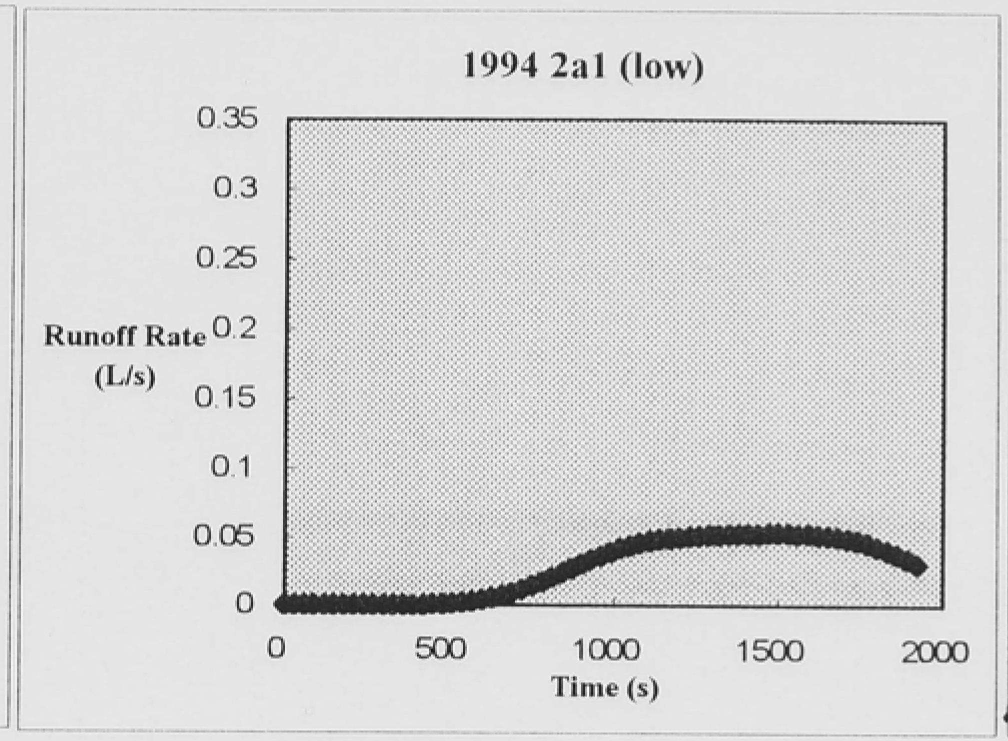


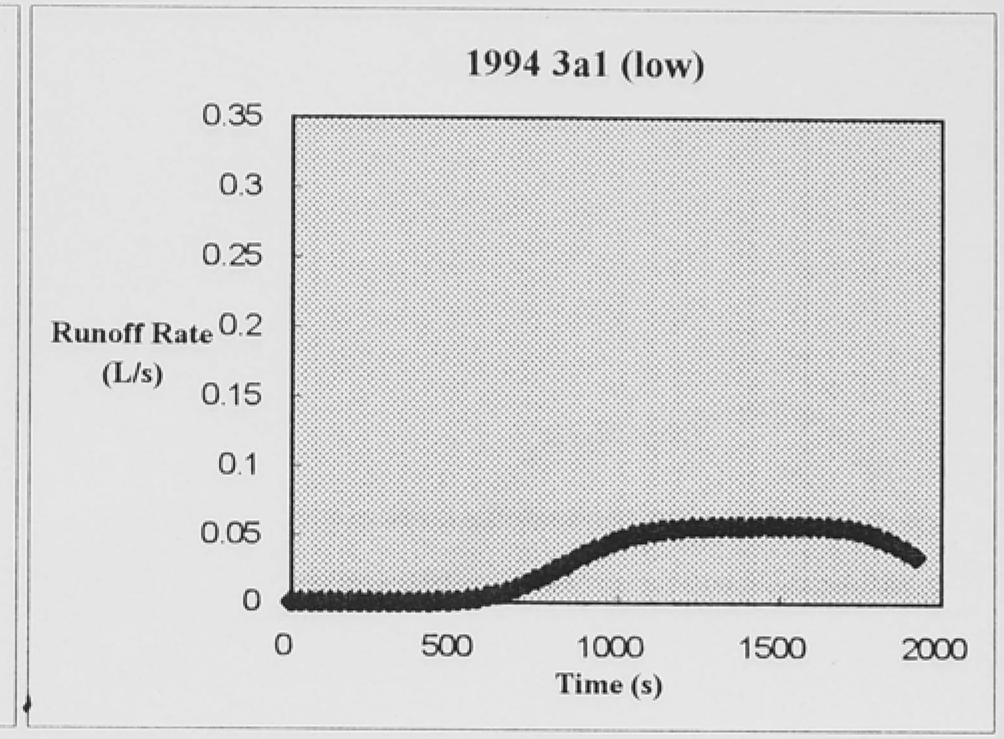
Mean slope: 5.2%

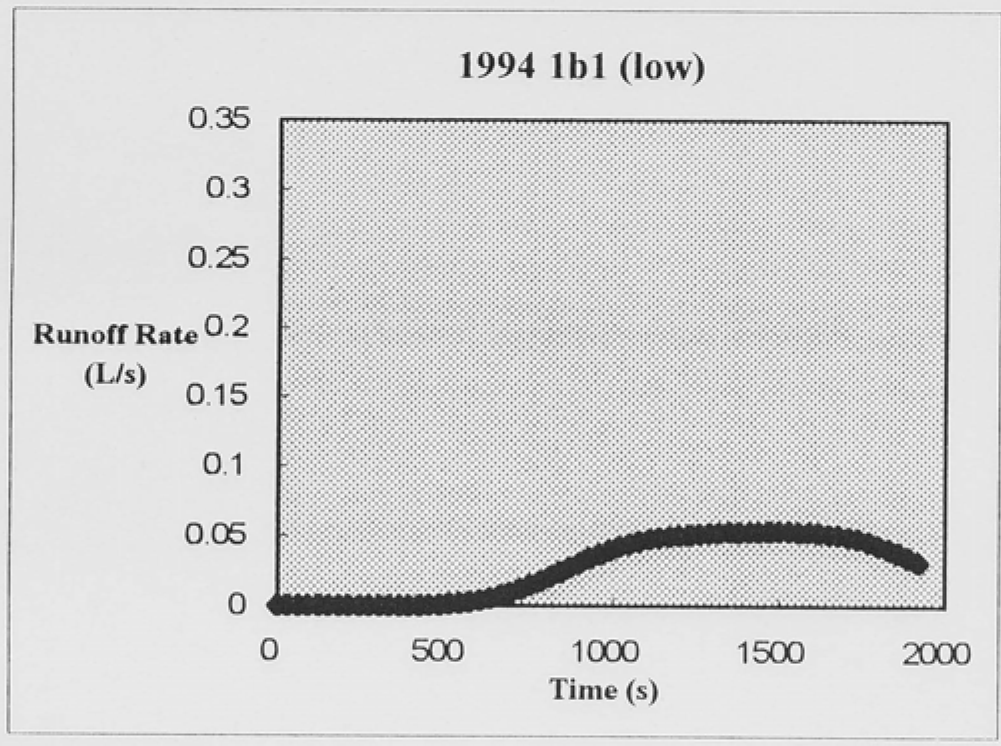
APPENDIX III

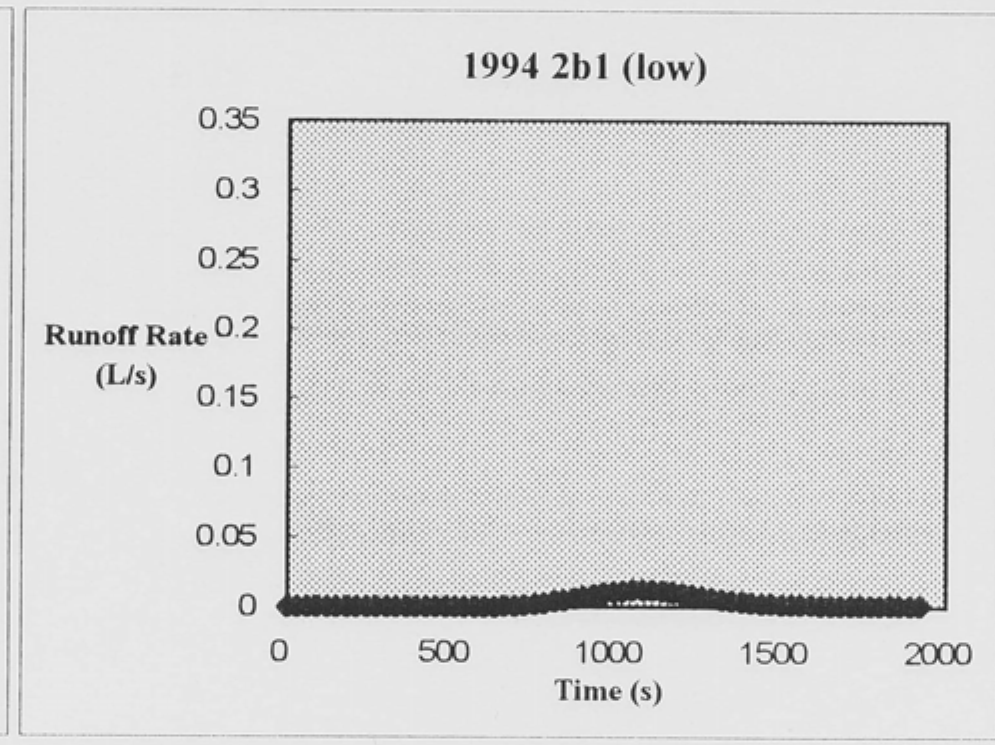
Erosion Plots Runoff Curves - Sampling at 30 s Intervals

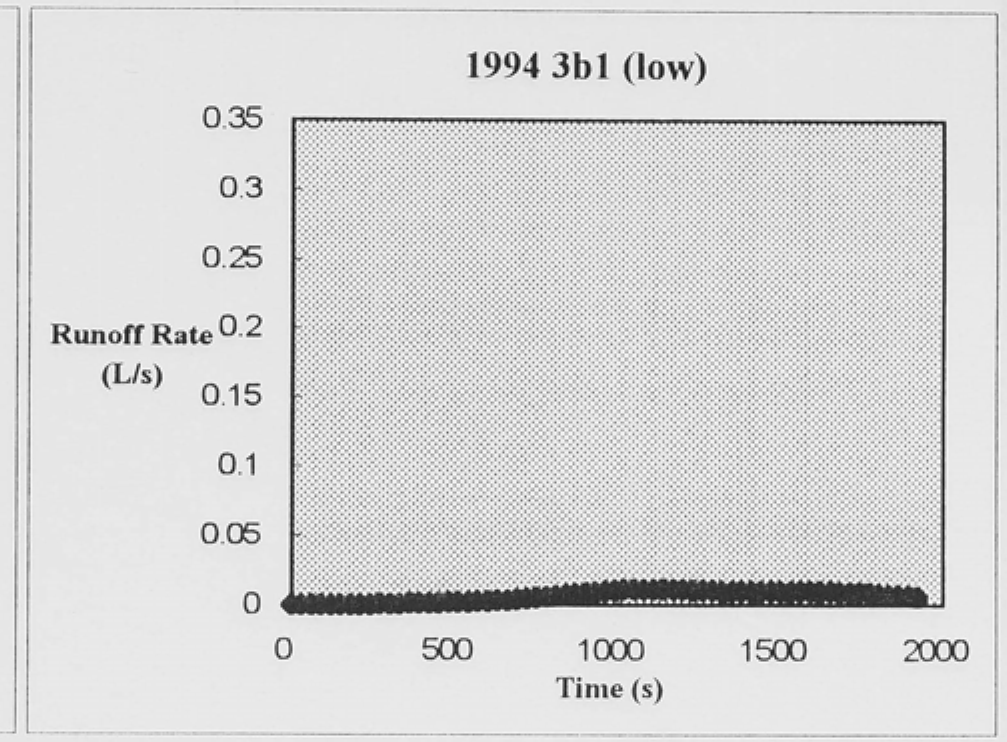

1994 1a1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
2500
Time (s)

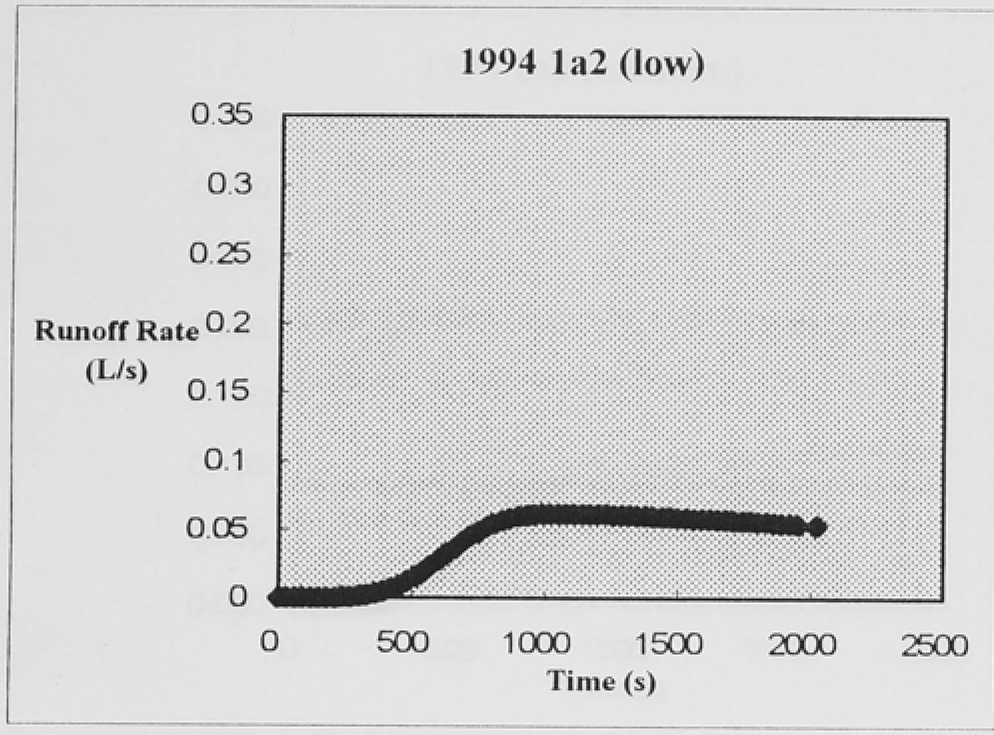

1994 2a1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

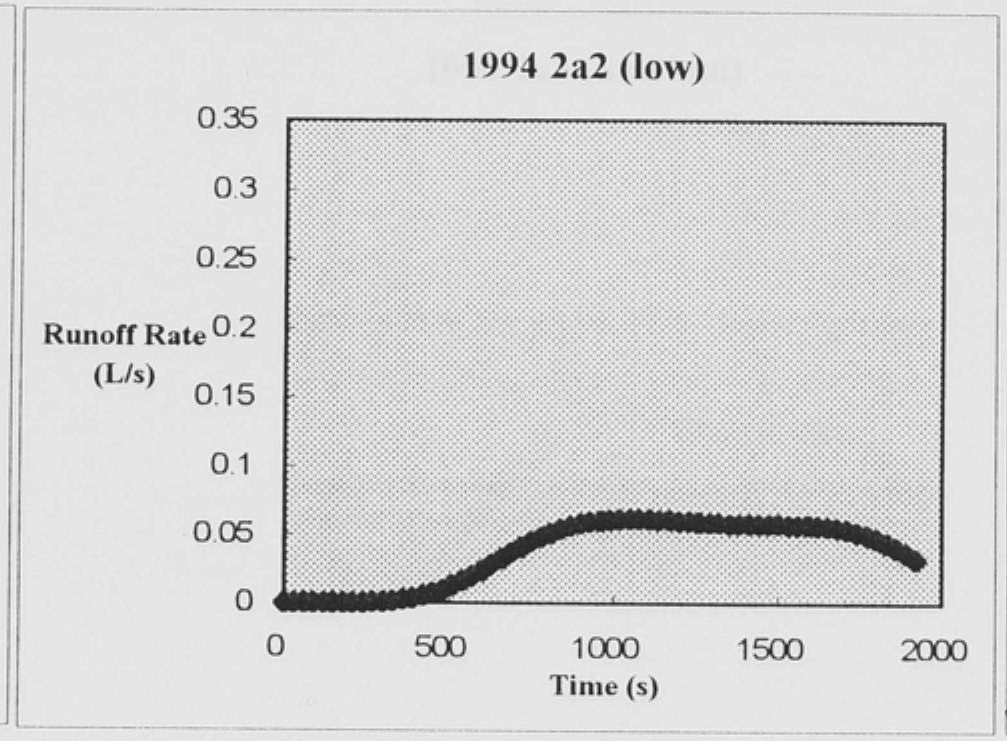

1994 3a1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

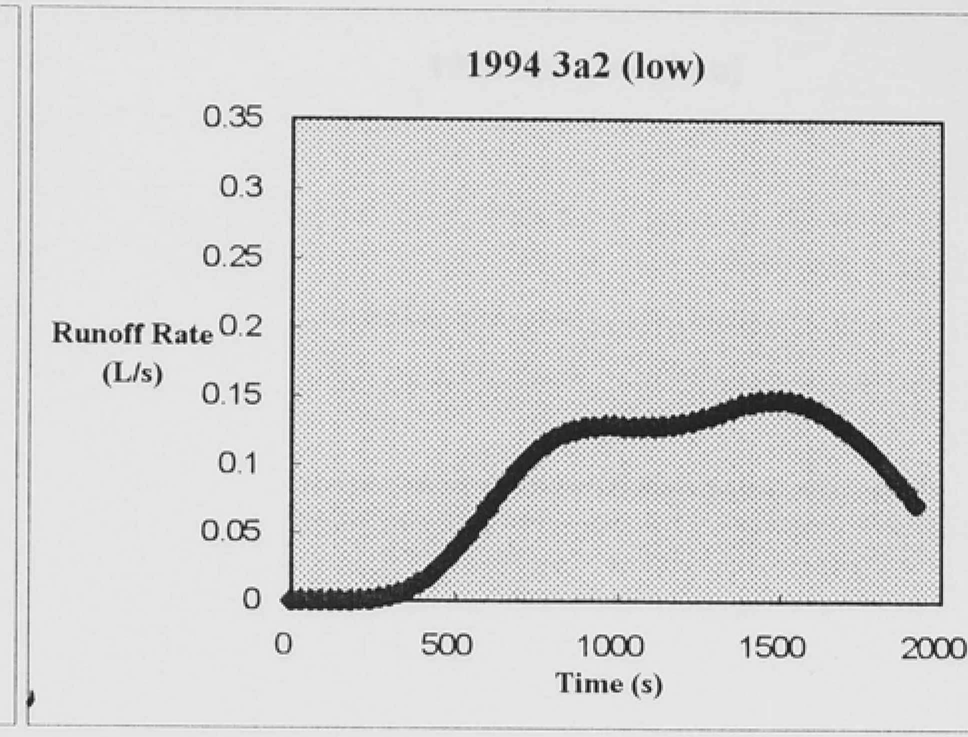

1994 1b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

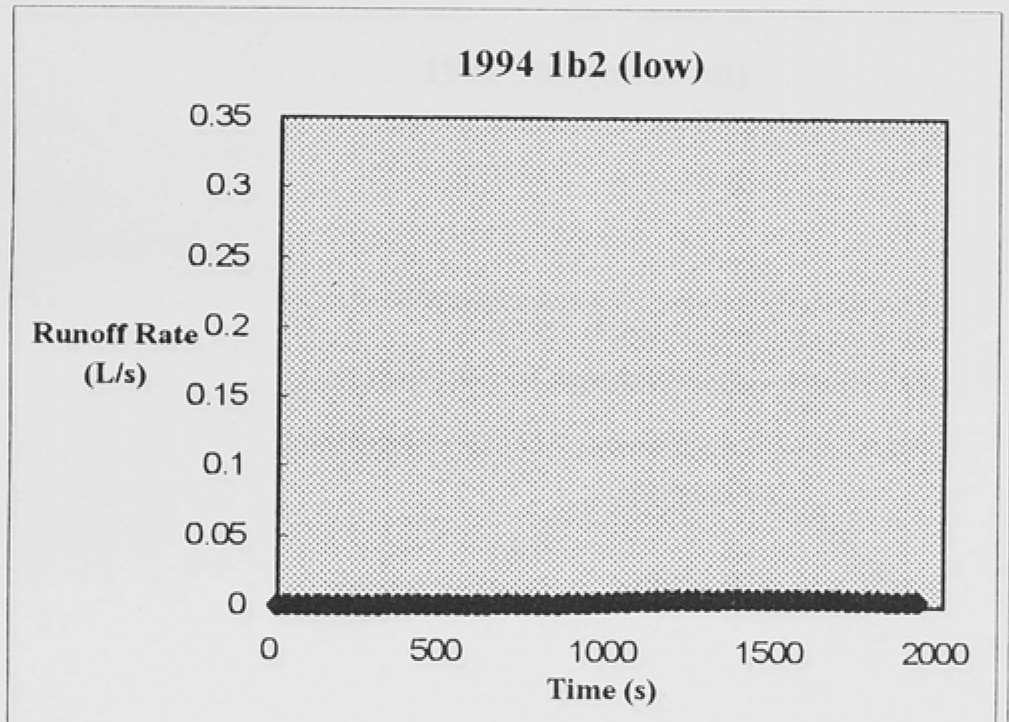

1994 2b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

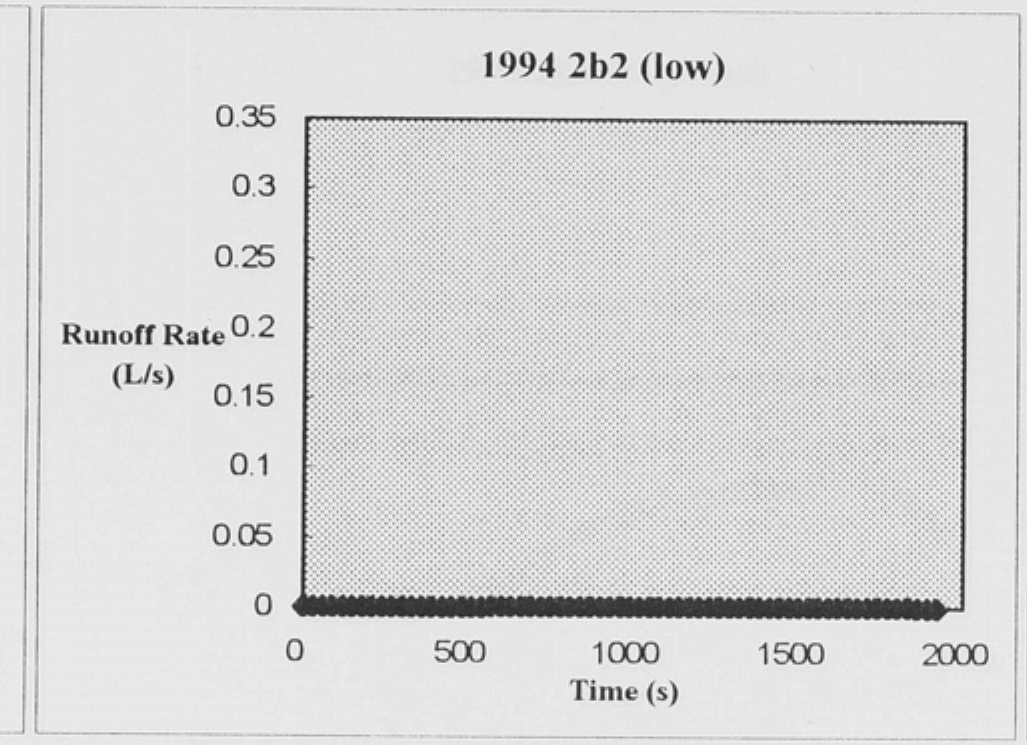

1994 3b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

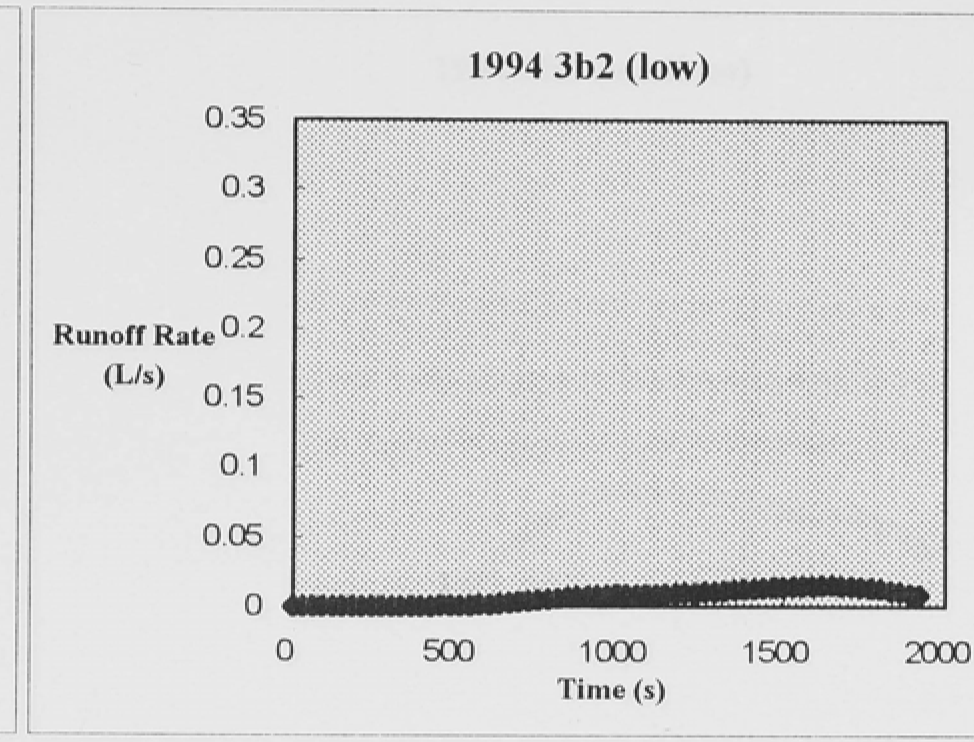

1994 1a2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000 2500
Time (s)

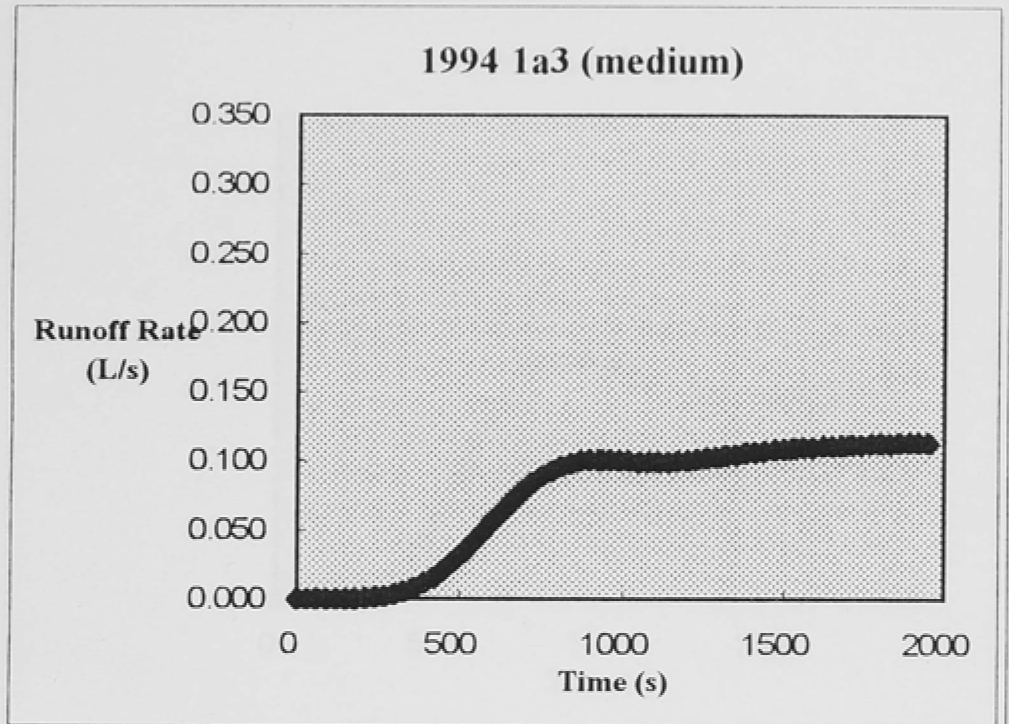

1994 2a2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

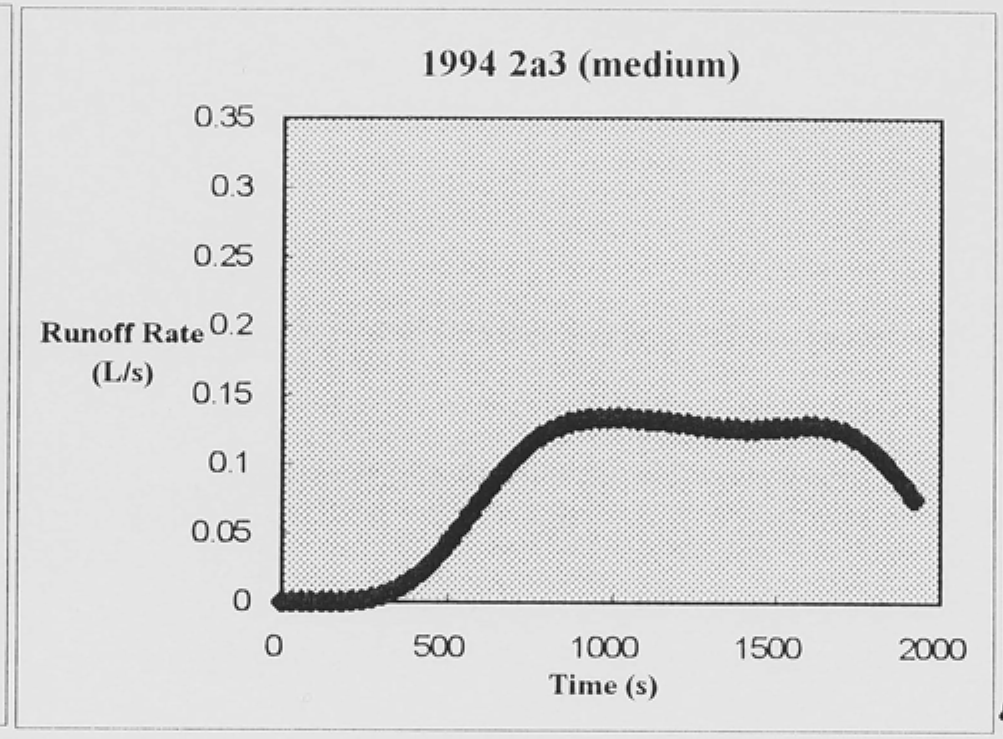

1994 3a2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

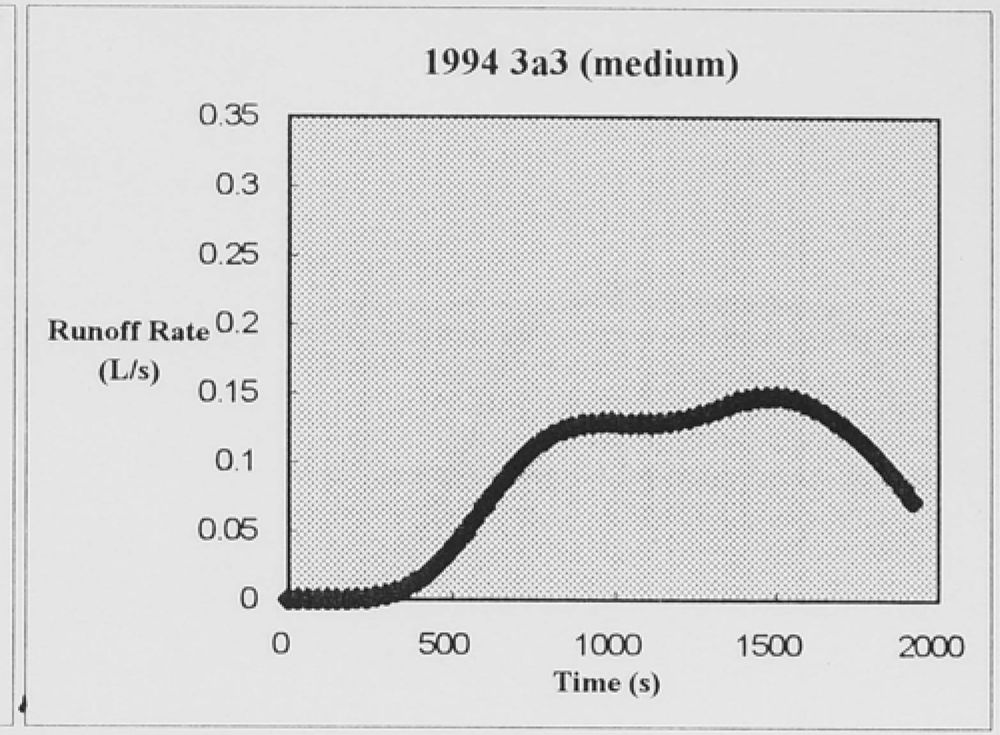

1994 1b2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

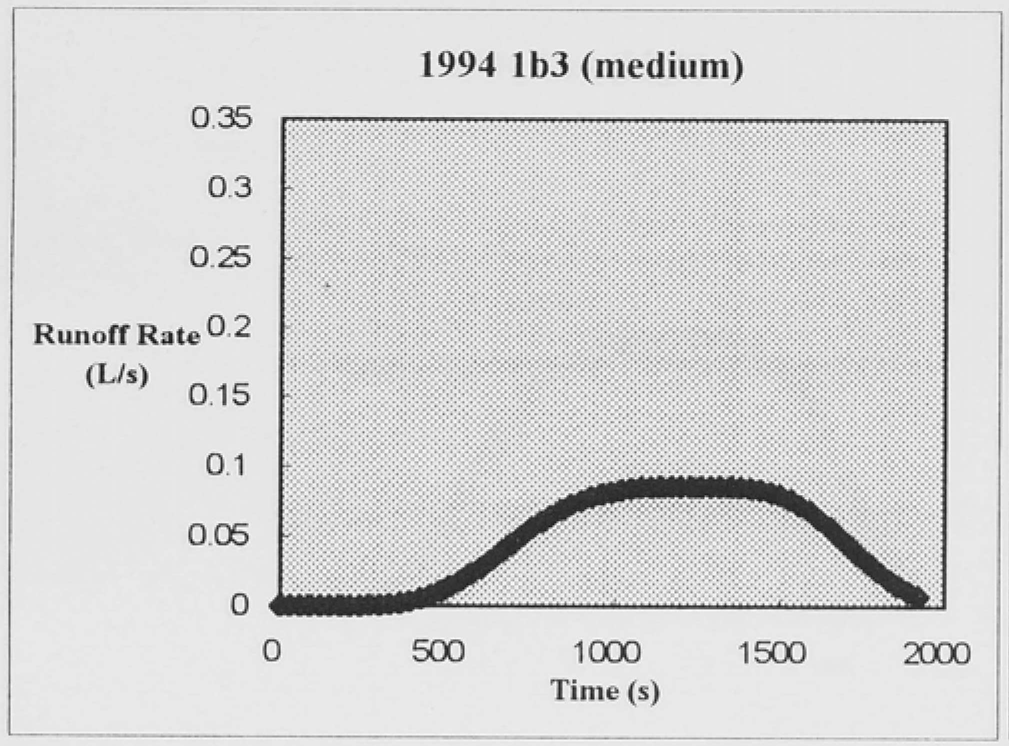

1994 2b2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

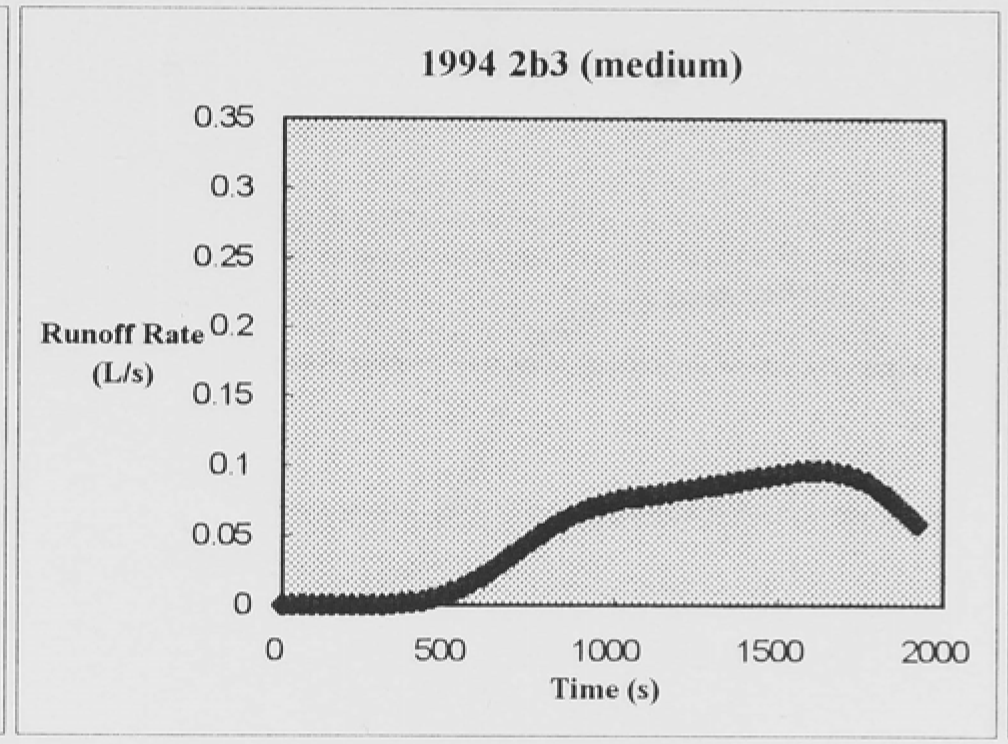

1994 3b2 (low)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

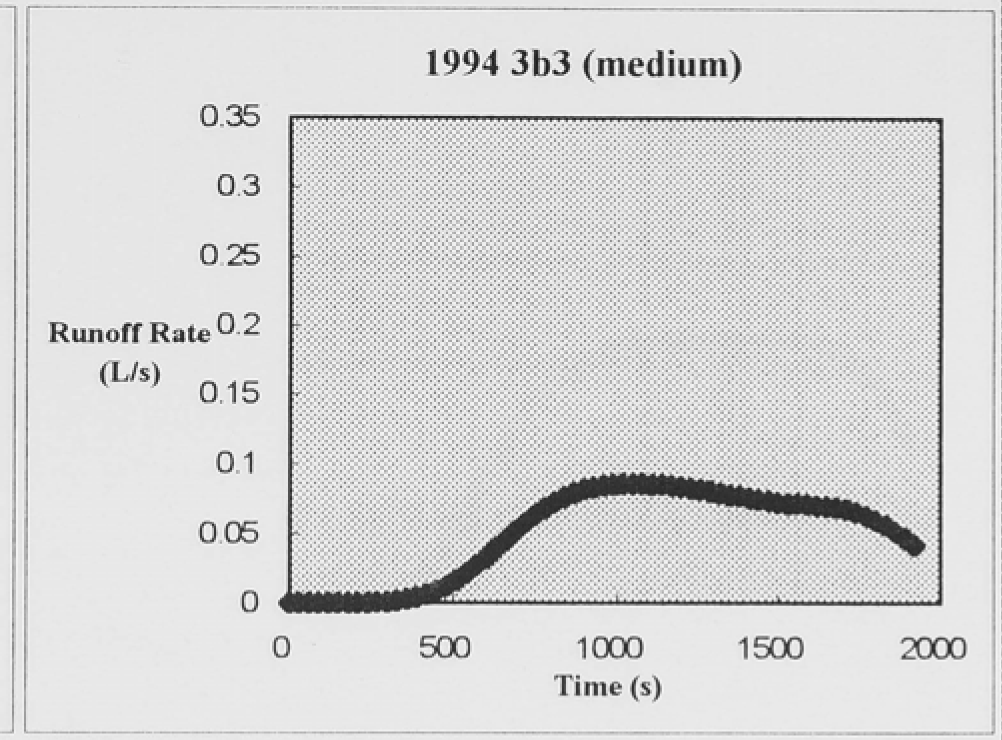

1994 1a3 (medium)
Runoff Rate (L/s)
0.000
0.050
0.100
0.150
0.200
0.250
0.300
0.350
0
500
1000
1500
2000
Time (s)

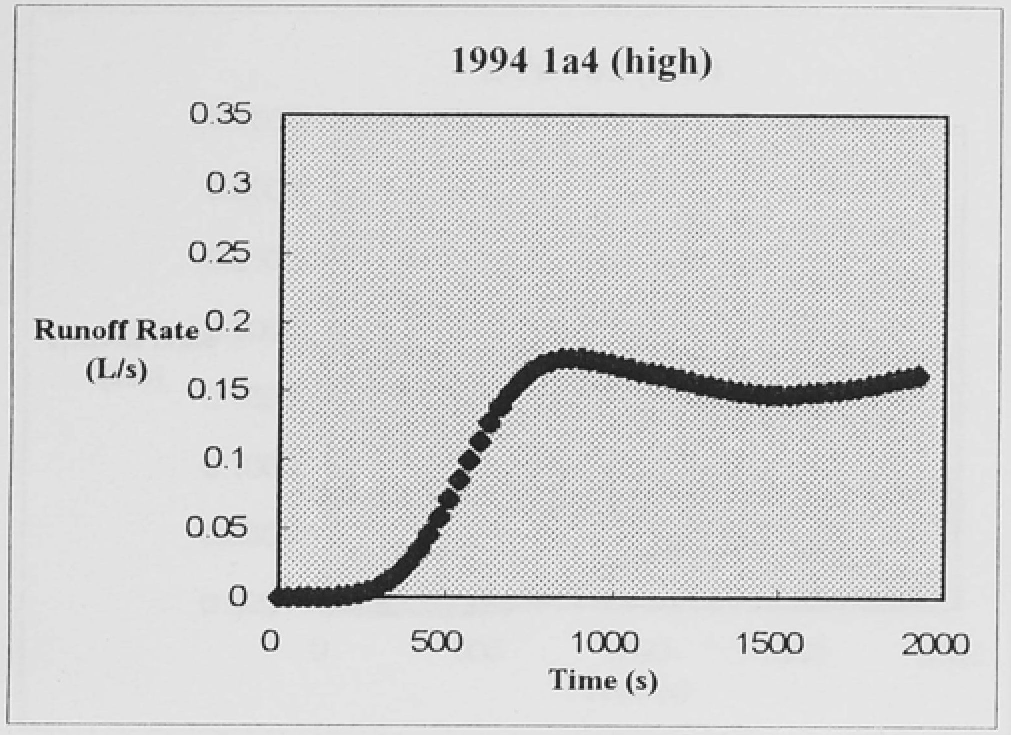

1994 2a3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

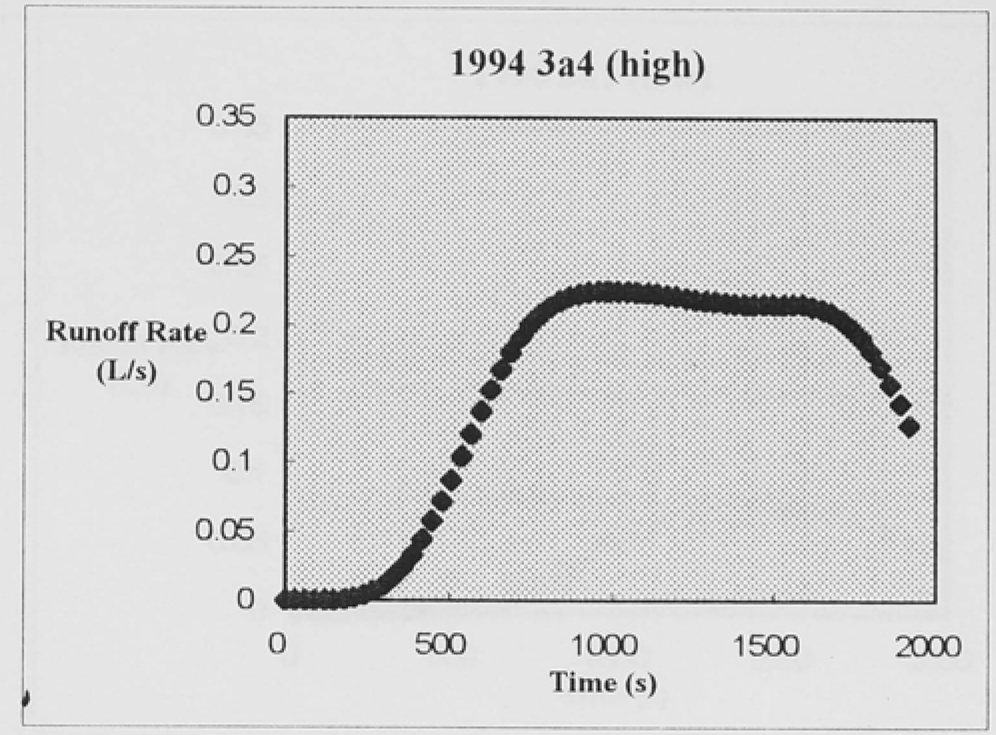

1994 3a3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

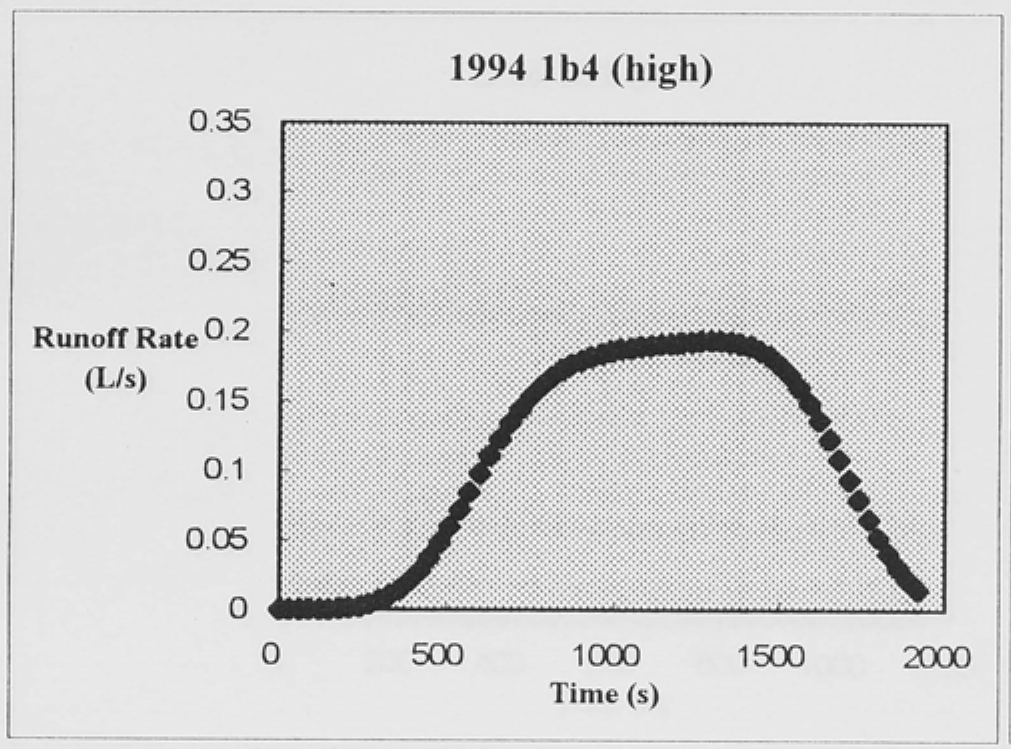

1994 1b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

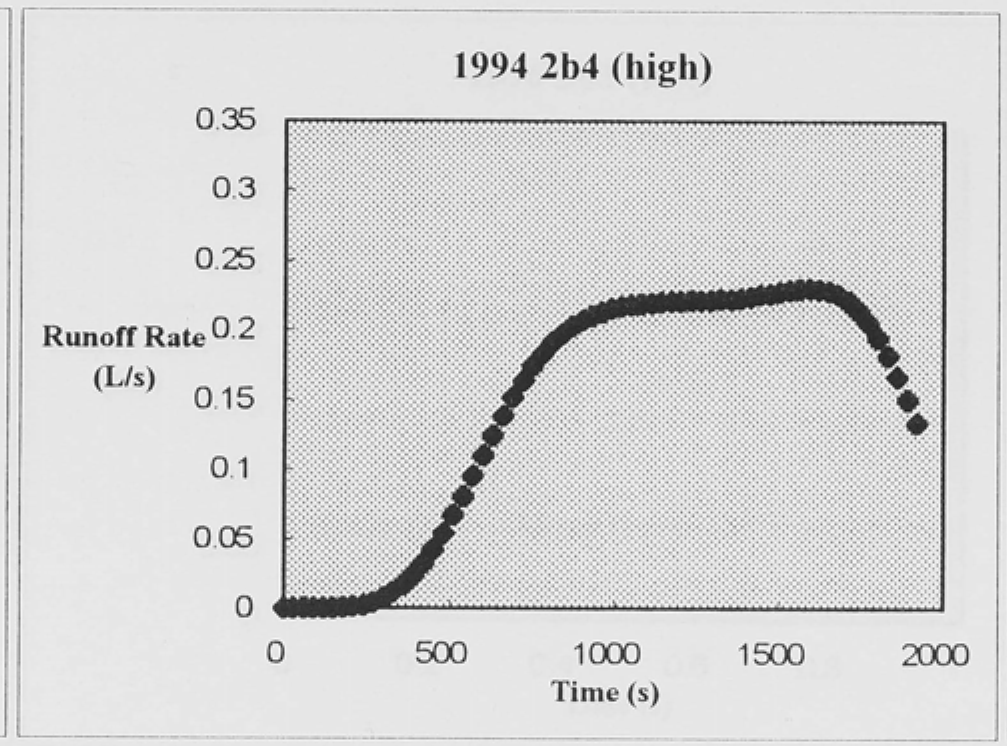

1994 2b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

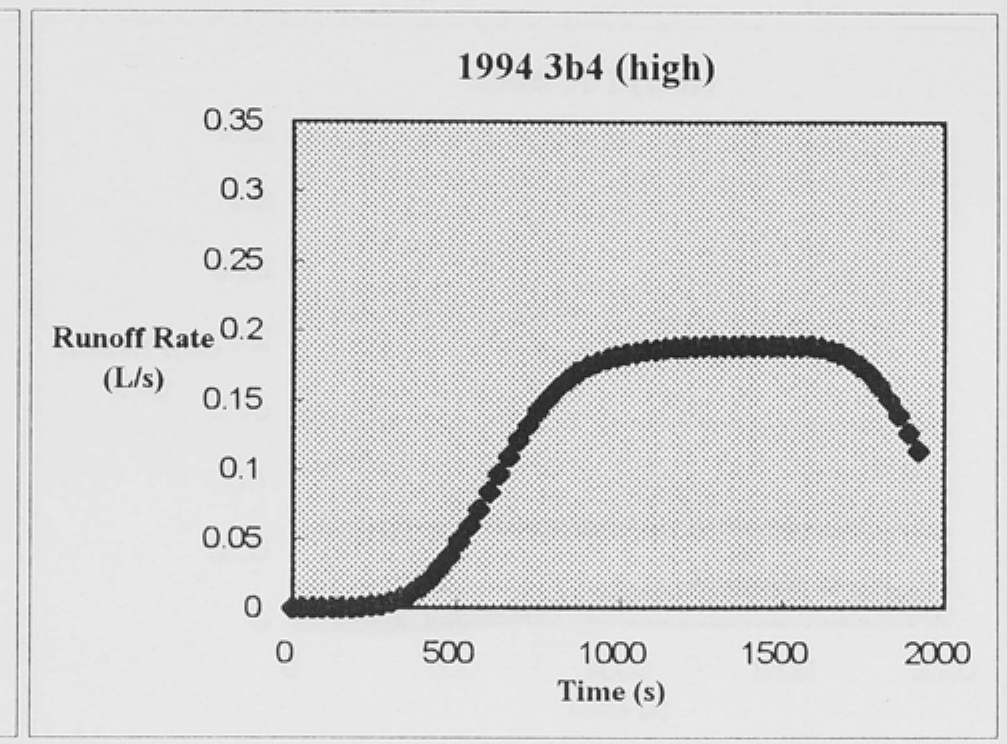

1994 3b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

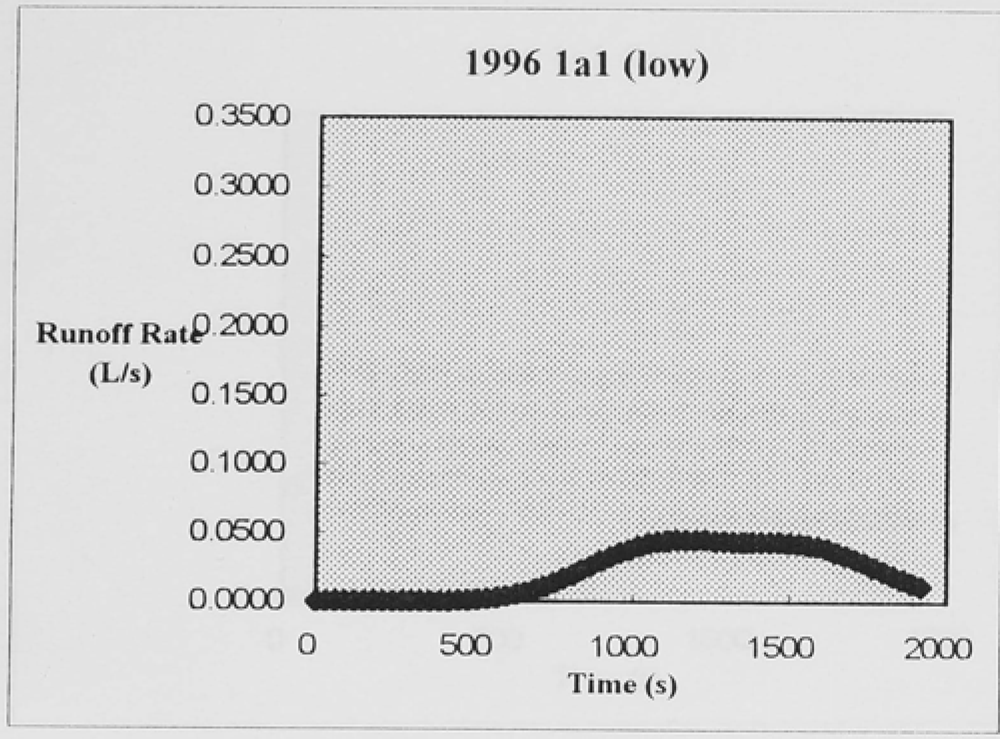

1994 1a4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

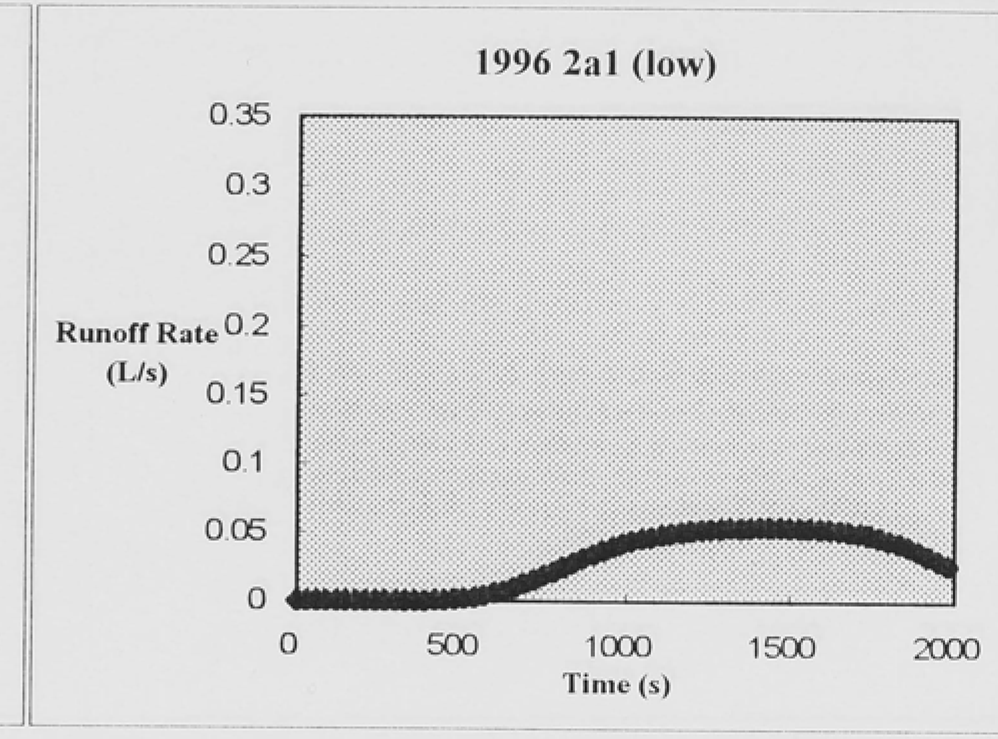

1994 3a4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

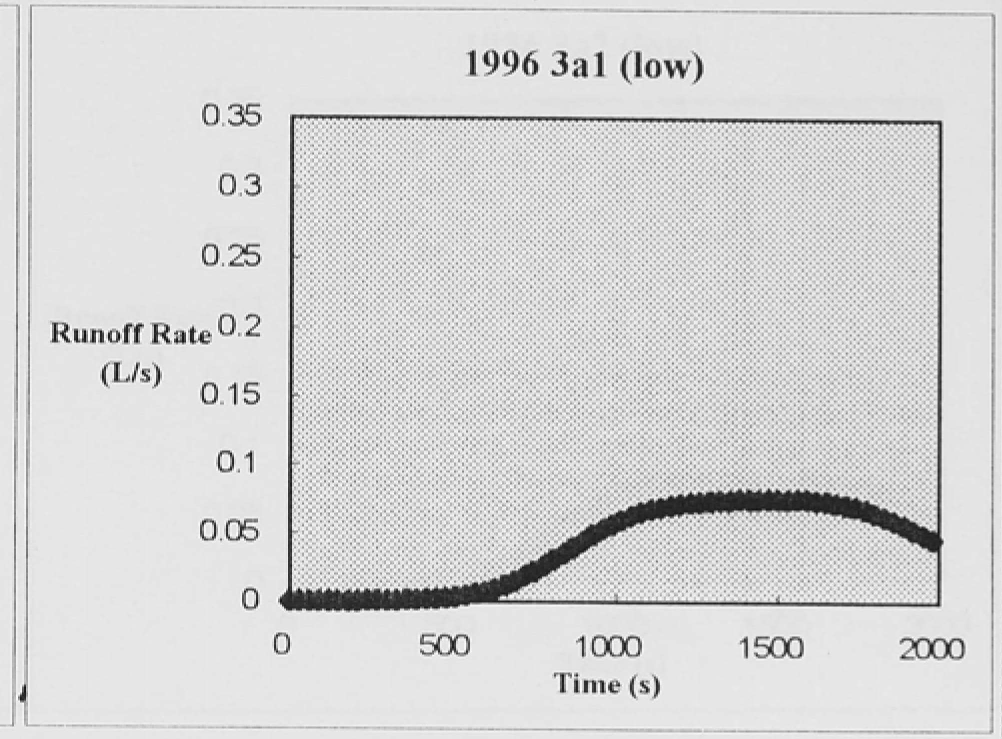

1994 1b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

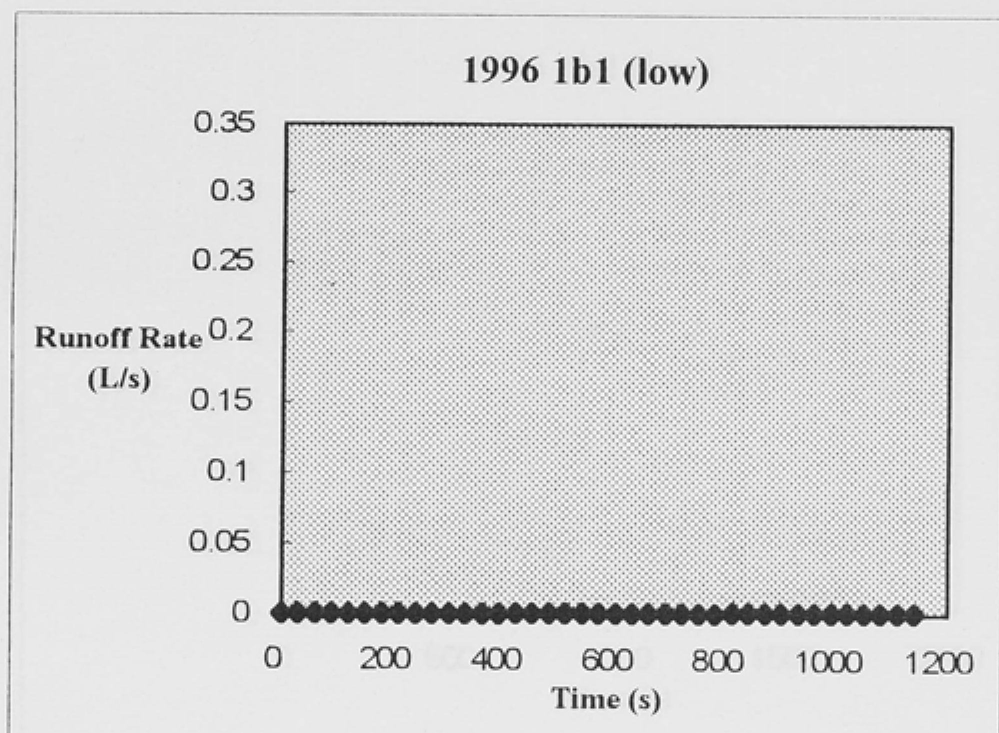

1994 2b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

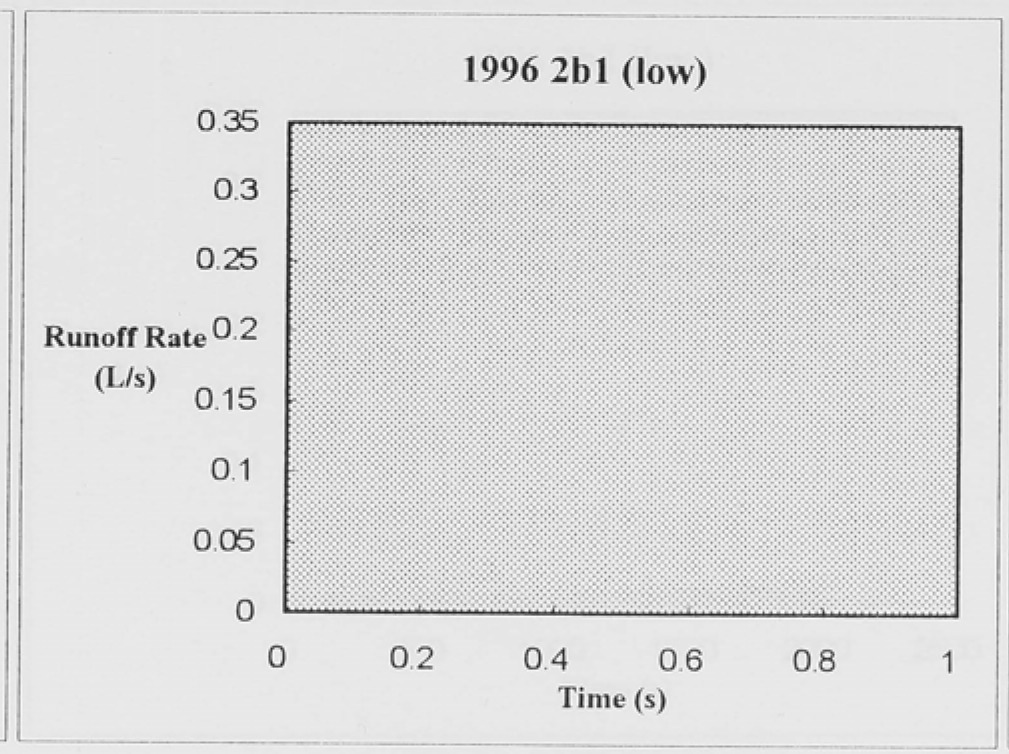

1994 3b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
0 500 1000 1500 2000
Time (s)

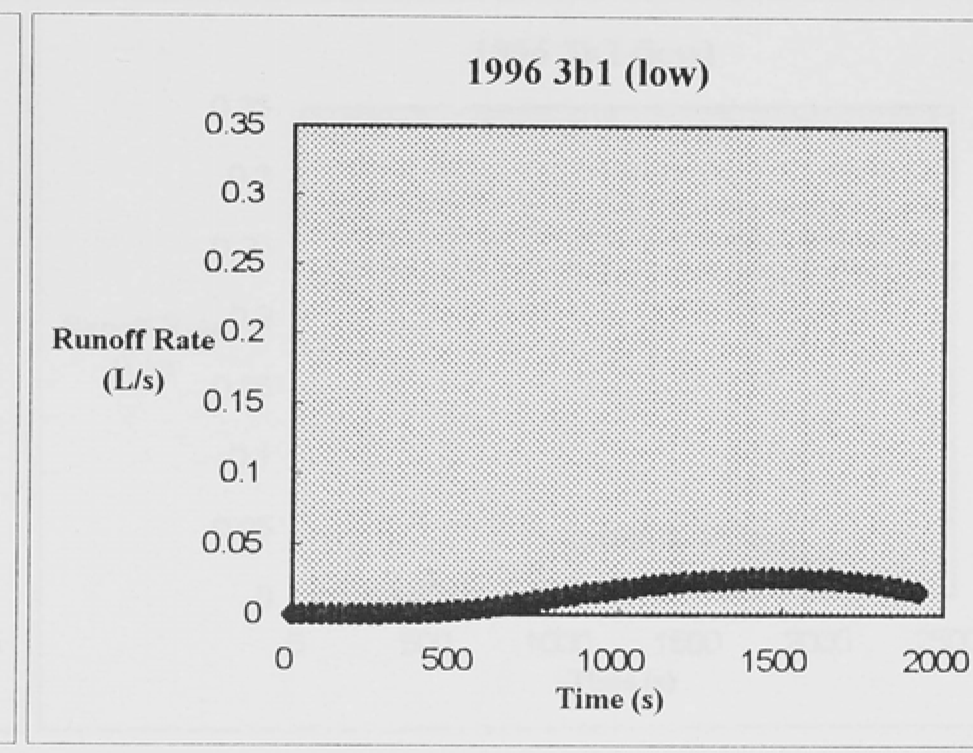

1996 1a1 (low)
Runoff Rate (L/s)
0.3500
0.3000
0.2500
0.2000
0.1500
0.1000
0.0500
0.0000
0
500
1000
1500
2000
Time (s)

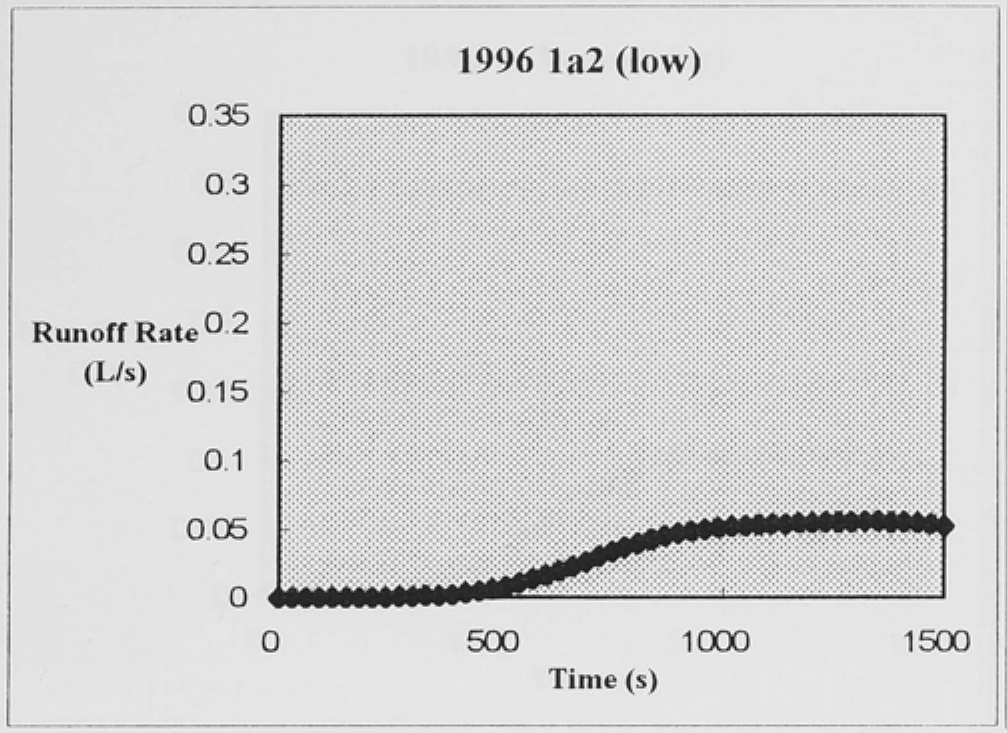

1996 2a1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

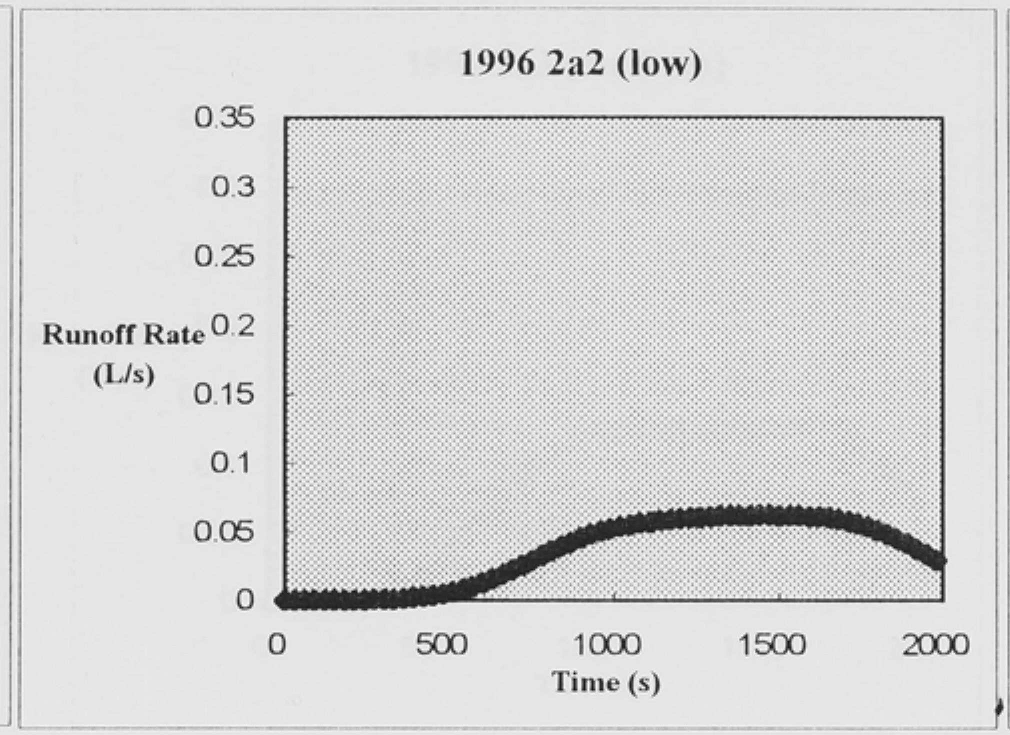

1996 3a1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

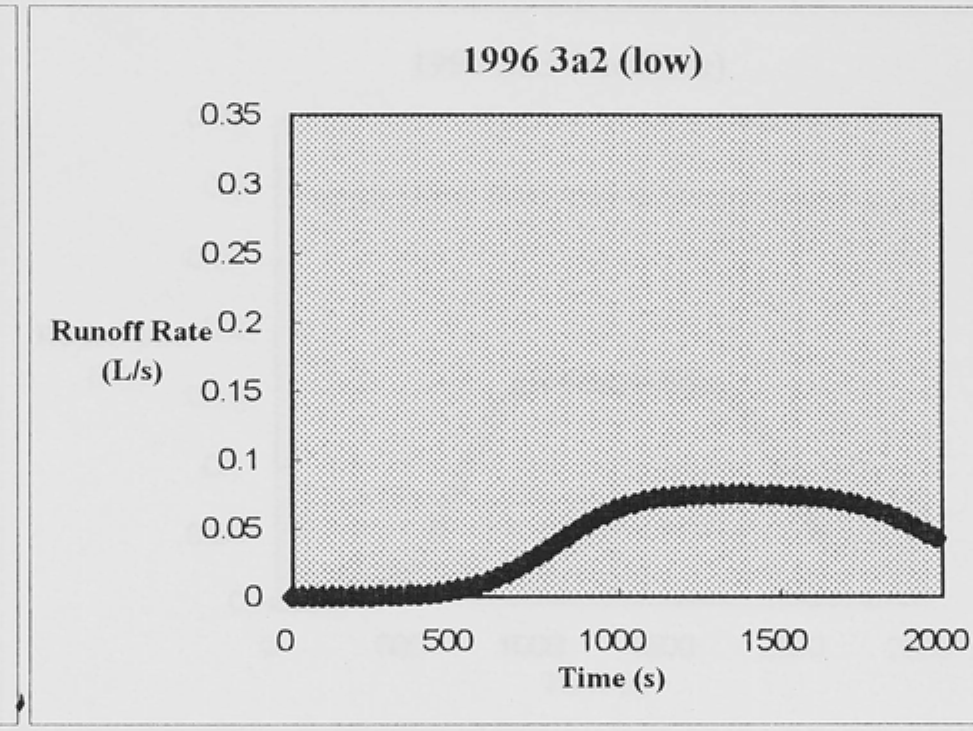

1996 1b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
1200
Time (s)

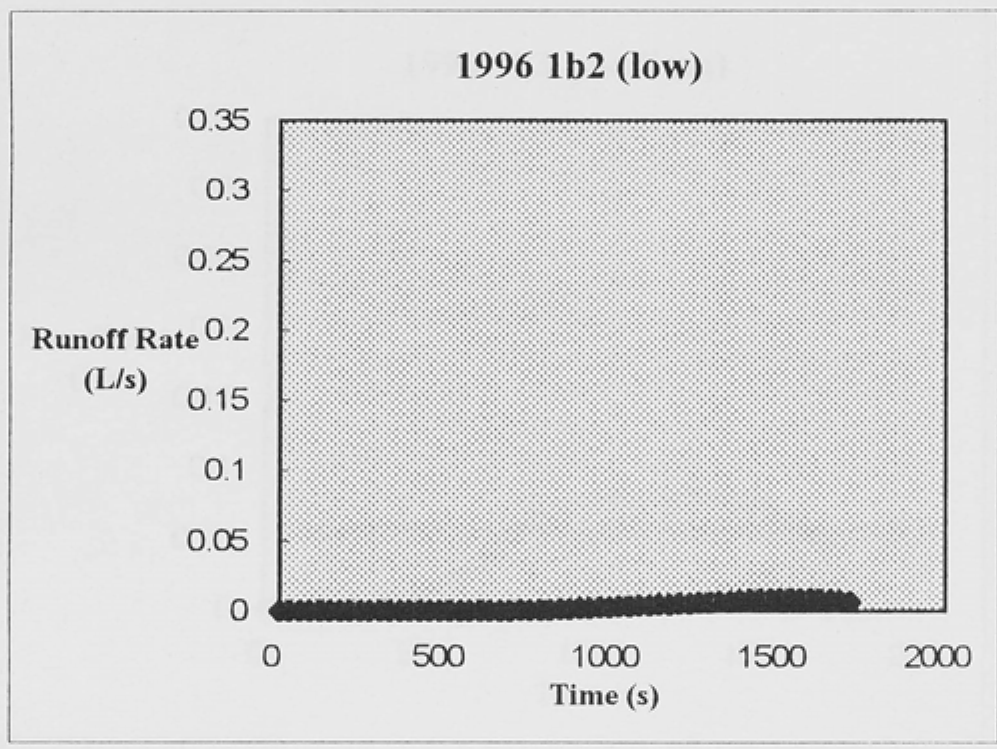

1996 2b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.2
0.4
0.6
0.8
1
Time (s)

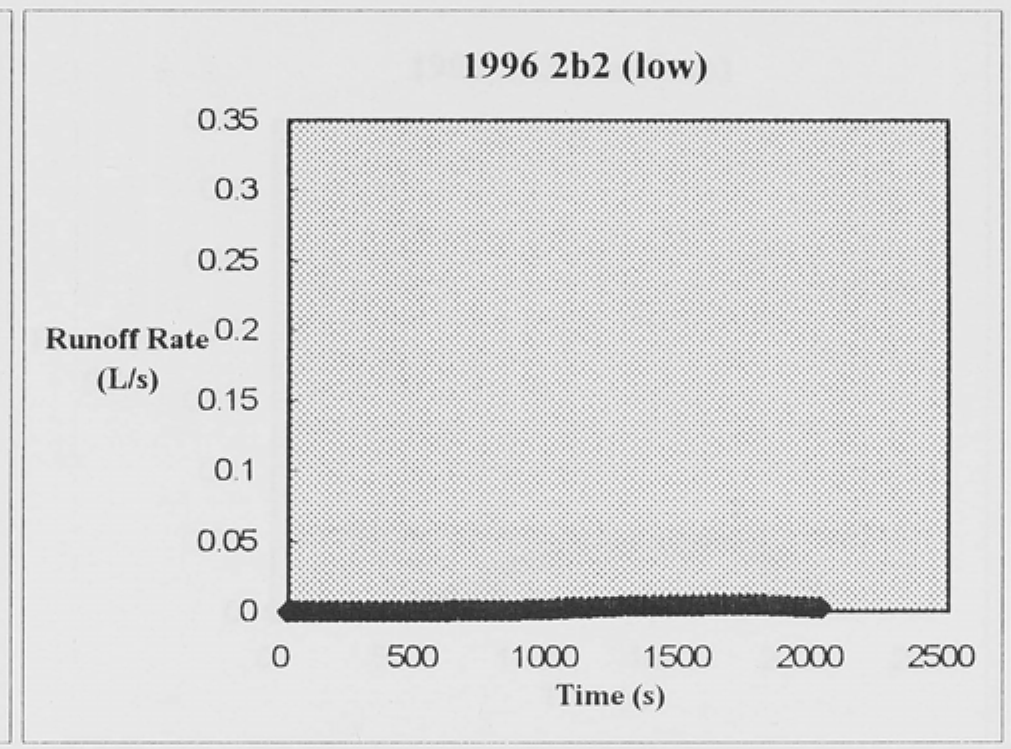

1996 3b1 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

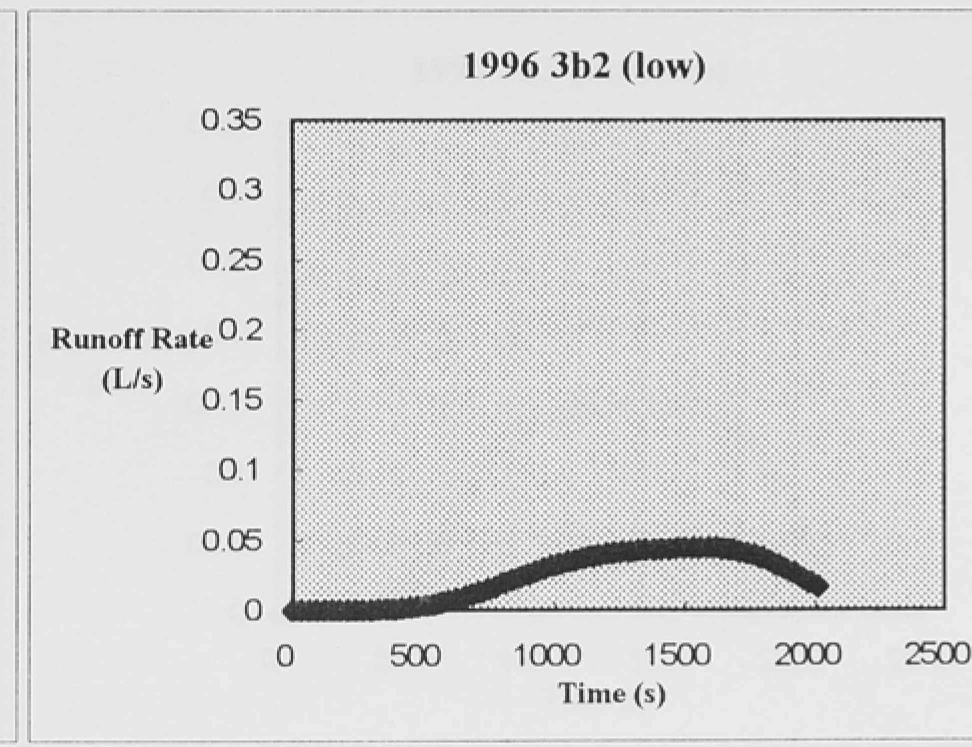

1996 1a2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
Time (s)

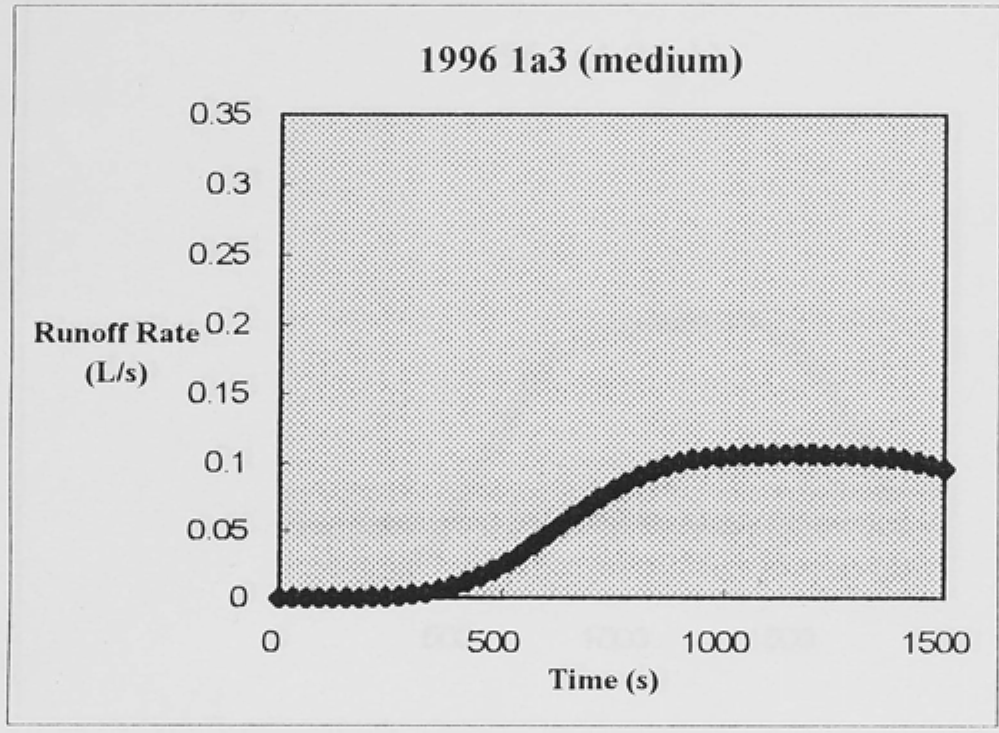

1996 2a2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

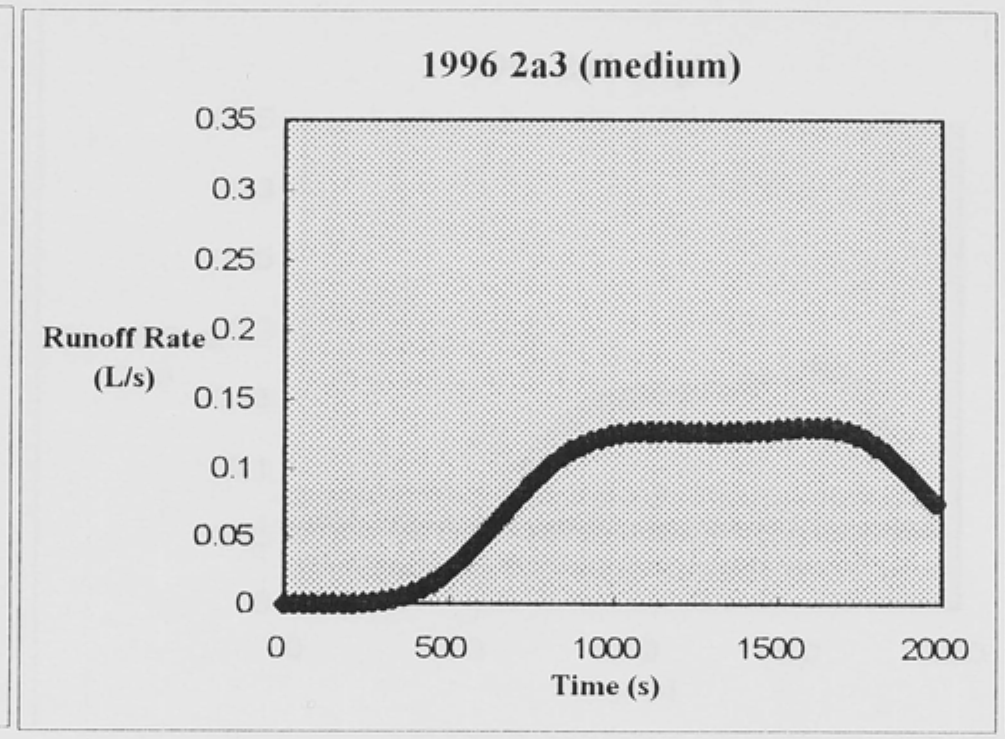

1996 3a2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

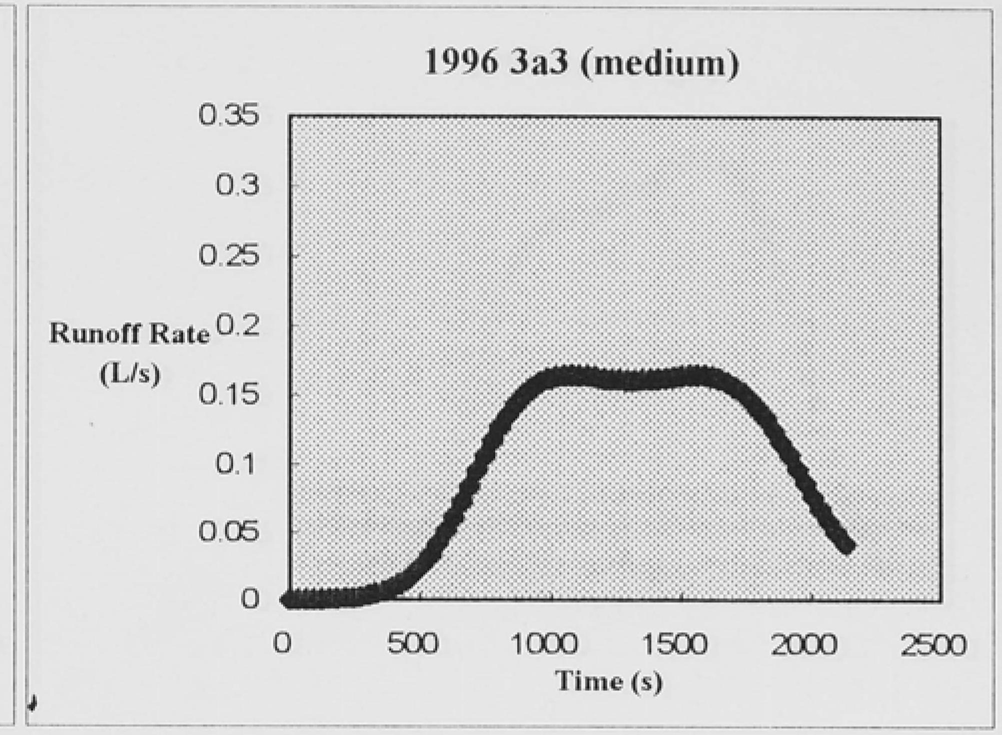

1996 1b2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
Time (s)

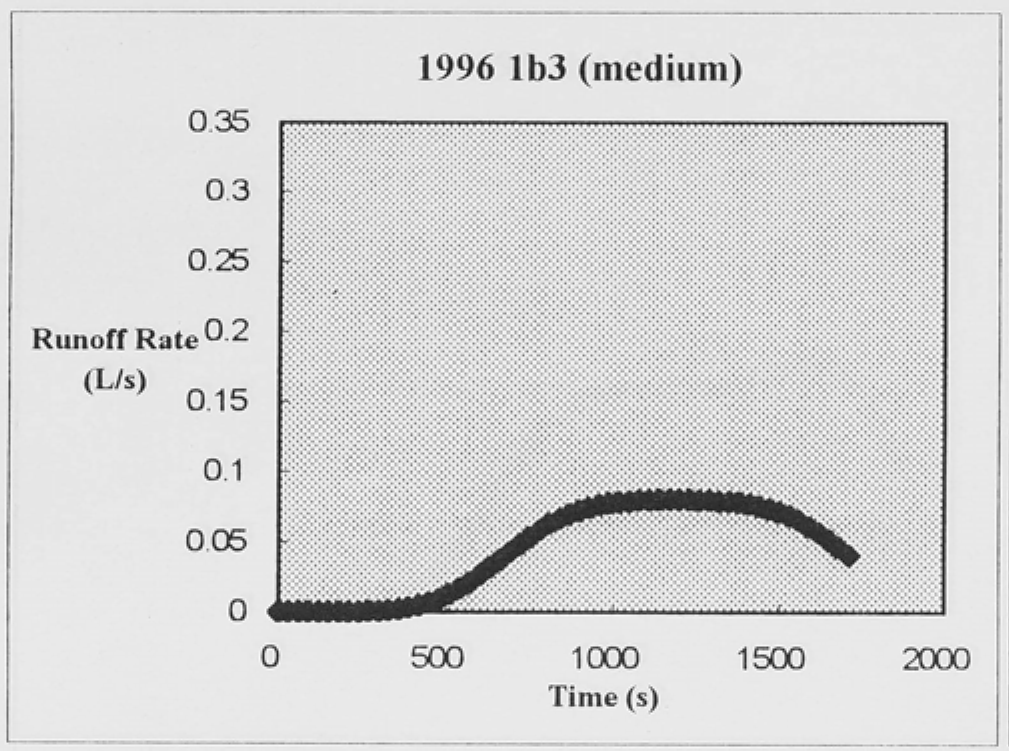

1996 2b2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
2500
Time (s)

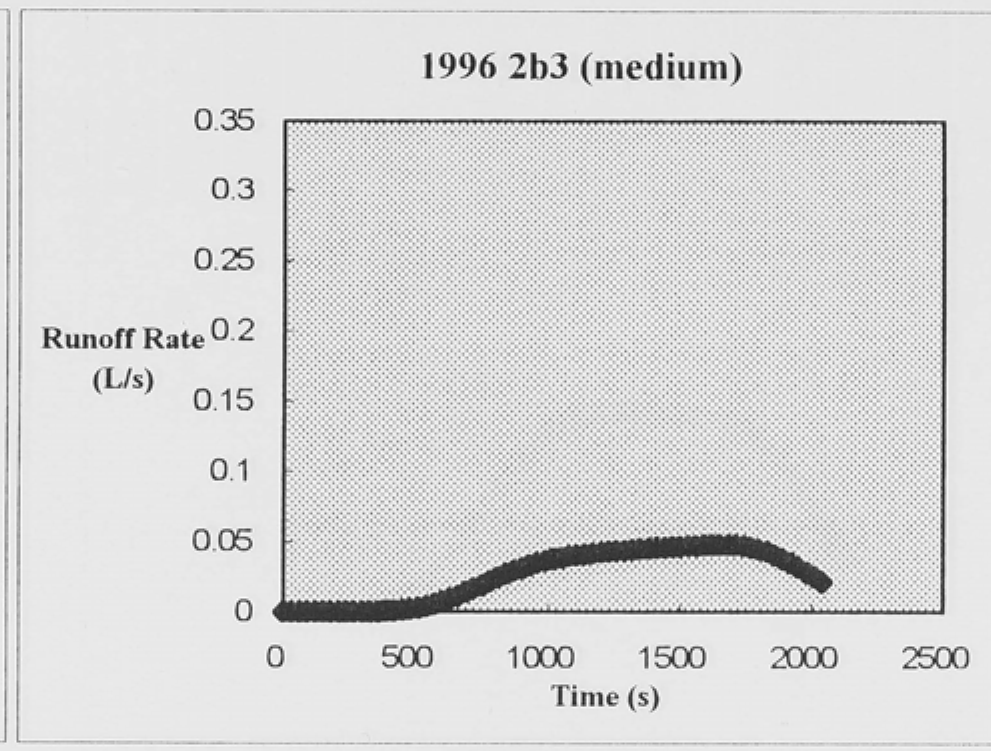

1996 3b2 (low)
Runoff Rate (L/s)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
500
1000
1500
2000
2500
Time (s)

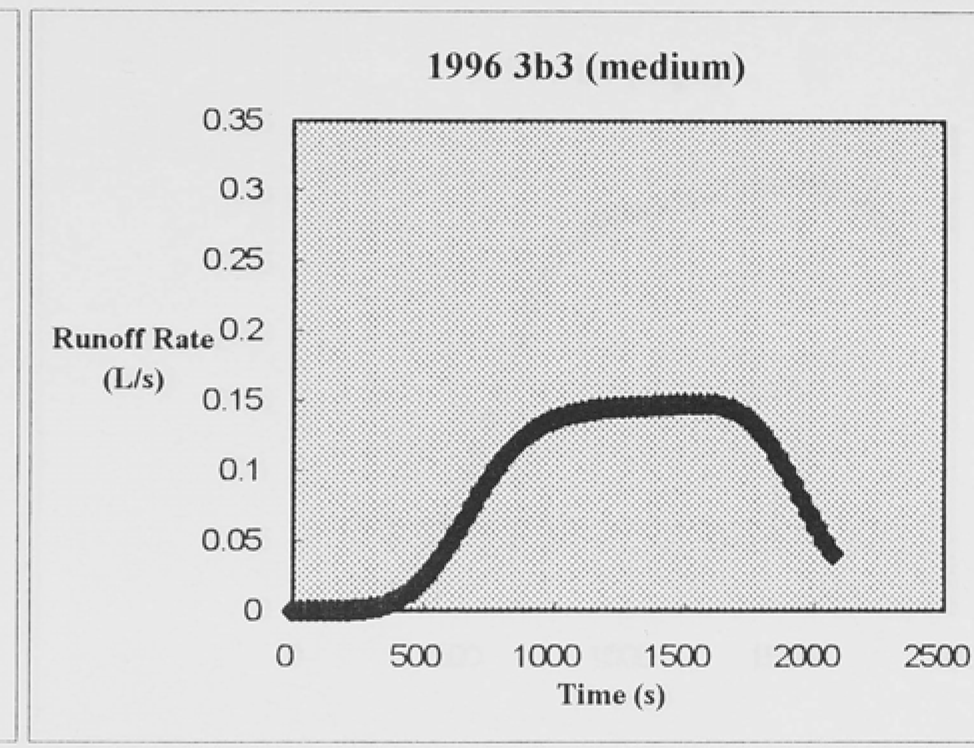

1996 1a3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
Time (s)

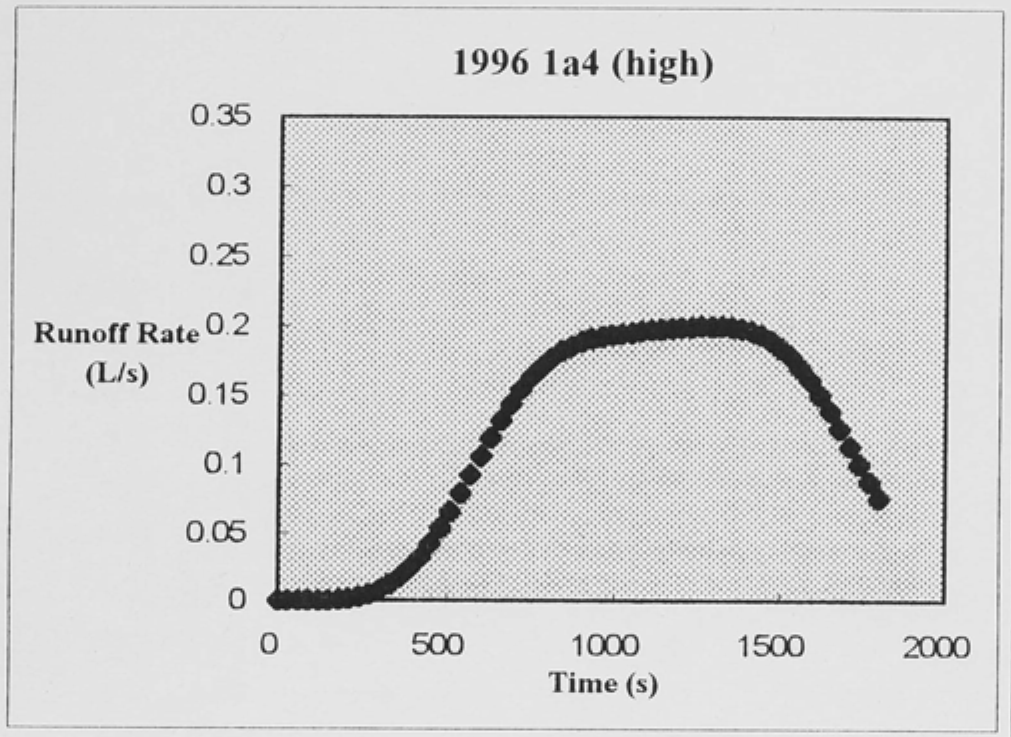

1996 2a3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

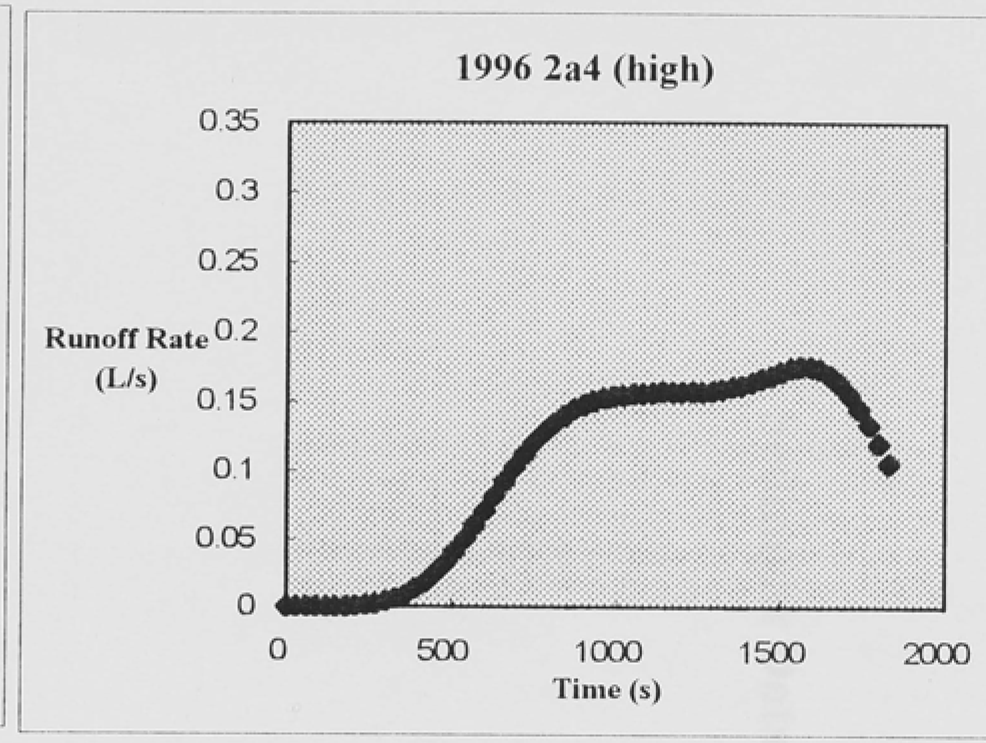

1996 3a3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
2500
Time (s)

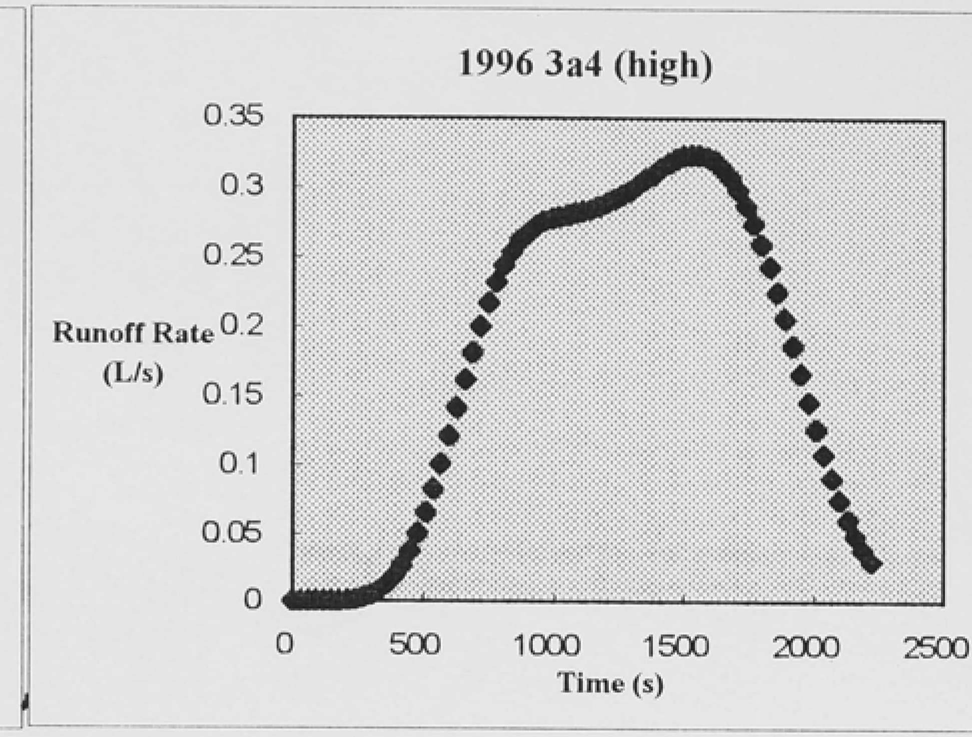

1996 1b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
Time (s)

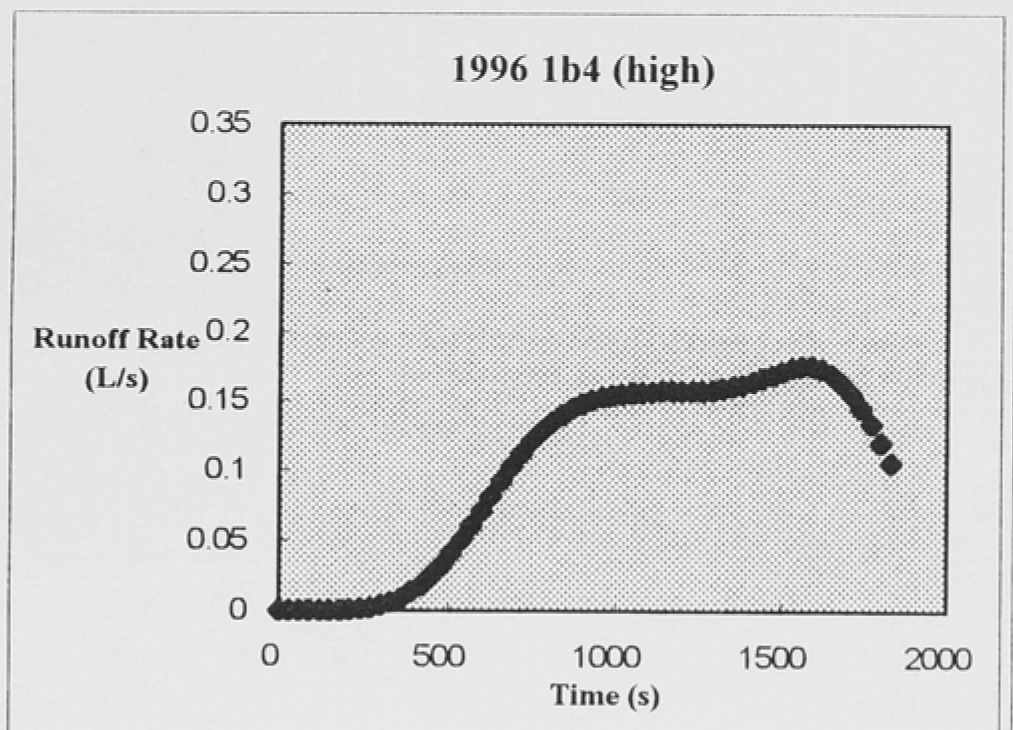

1996 2b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
2500
Time (s)

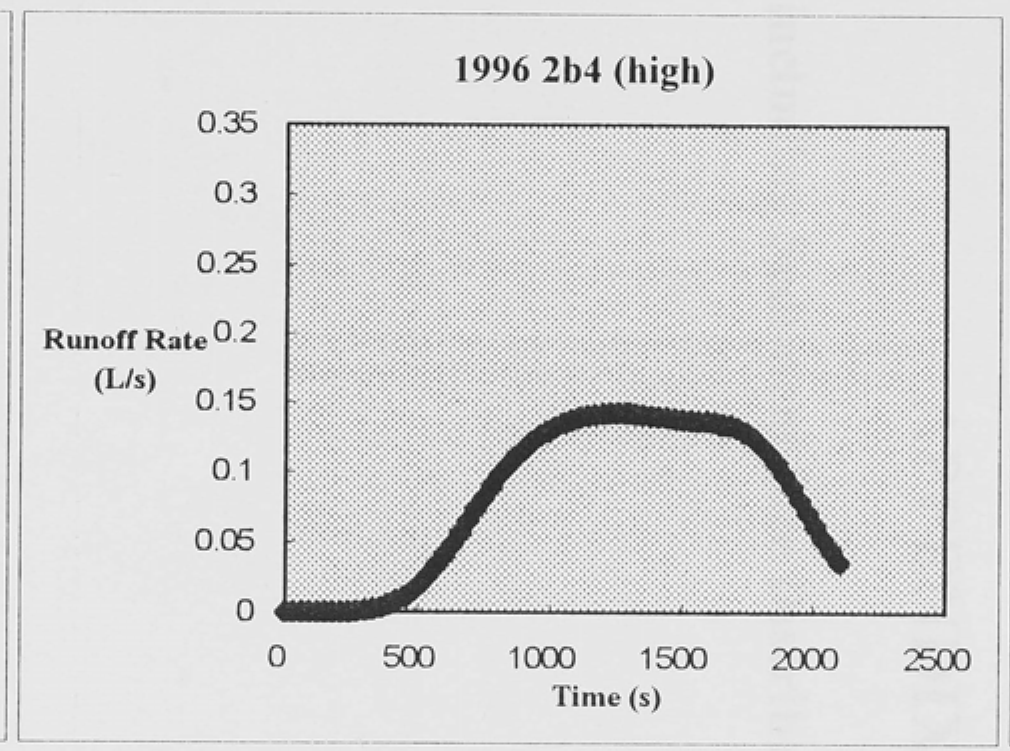

1996 3b3 (medium)
Runoff Rate (L/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
500
1000
1500
2000
2500
Time (s)

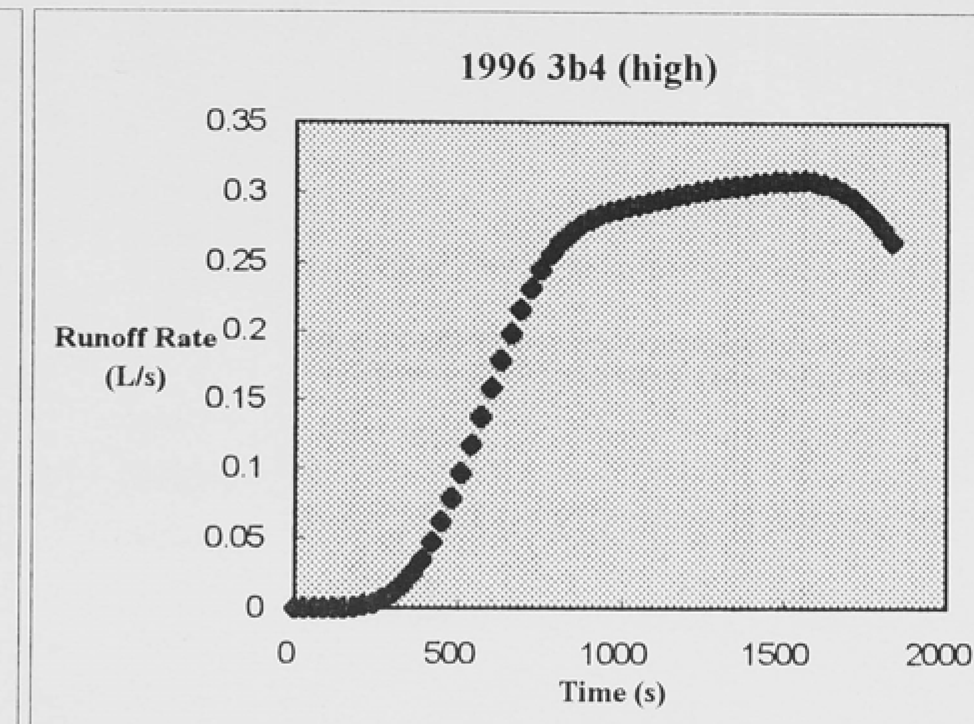

1996 1a4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000


1996 2a4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000


1996 3a4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000 2500


1996 1b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000


1996 2b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000 2500


1996 3b4 (high)
Runoff Rate (L/s)
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Time (s)
0 500 1000 1500 2000

APPENDIX IV

Sediment Data including Sediment Size Distribution

Sediment Concentrations of individual samples (other than sieved samples)

1994

#	SedConc (g/L)	#	SedConc (g/L)	#	SedConc (g/L)	#	SedConc (g/L)
Run1a1		Run1b1		Run2a1		Run2b1	
A01	6.39			A25	3.59		
A02	2.81	no runoff		A26	4.43	no runoff	
A03	2.39			A27	3.73		
A04	2.15			A28	3.66		
A05	2.20			A29	2.51		
A06	2.05			A30	2.29		
Run1a2		Run1b2		Run2a2		Run2b2	
A07	1.61			A31	1.85		
A08	1.83	no runoff		A32	2.43	no runoff	
A09	2.11			A33	2.78		
A10	1.72			A34	2.62		
A11	1.99			A35	2.58		
A12	1.73			A36	2.08		
Run1a3		Run1b3		Run2a3		Run2b3	
A13	2.31	B01	2.92	A37	2.78	B12	3.05
A14	2.33	B02	2.79	A38	3.25	B13	1.93
A15	2.34	B03	2.47	A39	3.07	B14	1.31
A16	1.81	B04	2.79	A40	2.76	B15	1.15
A17	2.12	B05	3.34	A41	3.54	B16	1.03
A18	2.91			A42	2.50	B17	1.20
Run1a4		Run1b4		Run2a4		Run2b4	
A19	2.19	B06	2.72			B18	1.51
A20	2.35	B07	2.22	no run		B19	1.10
A21	3.10	B08	1.91			B20	1.28
A22	2.53	B09	2.73			B21	1.07
A23	2.88	B10	2.33			B22	1.57
A24	2.77	B11	2.27			B23	1.14

1996

#	SedConc (g/L)	#	SedConc (g/L)	#	SedConc (g/L)	#	SedConc (g/L)
Run1a1		Run1b1		Run3a1		Run3b1	
A101	1.053			A301	1.260	B301	2.15
A102	0.873	no runoff		A302	0.675	B302	2.16
A103	0.266			A303	0.379	B303	2.24
A104	0.715			A304	0.405	B304	1.79
A105	0.379			A305	0.253		
A106	0.525			A306	0.384		
Run1a2		Run1b2		Run3a2		Run3b2	
A107	0.263			A307	0.630	B305	1.85
A108	0.246	no runoff		A308	0.394	B306	1.21
A109	0.235			A309	0.253	B307	1.10
A110	0.748			A310	0.227	B308	1.01
A111	0.823			A311	0.112	B309	0.81
A112	0.623			A312	0.399	B310	0.79
Run1a3		Run1b3		Run3a3		Run3b3	
A113	0.399	B201	0.91	A313	0.810	B311	1.36
A114	0.623	B202	0.84	A314	0.460	B312	0.74
A115	1.128	B203	0.80	A315	0.114	B313	1.43
A116	0.505	B204	0.51	A316	0.353	B314	1.12
A117	0.657	B205	0.59	A317	0.227	B315	2.22
A118	0.256	B206	1.11	A318	0.266	B316	1.25
Run1a4		Run1b4		Run3a4		Run3b4	
A119	0.661	B207	1.17	A319	0.588	B317	1.34
A120	0.932	B208	1.07	A320	0.374	B318	2.25
A121	0.962	B209	1.14	A321	0.487	B319	2.37
A122	0.865	B210	0.87	A322	0.379	B320	2.82
A123	0.721	B211	1.18	A323	0.581	B321	2.18
A124	0.758	B212	1.31	A324	0.721	B322	1.40

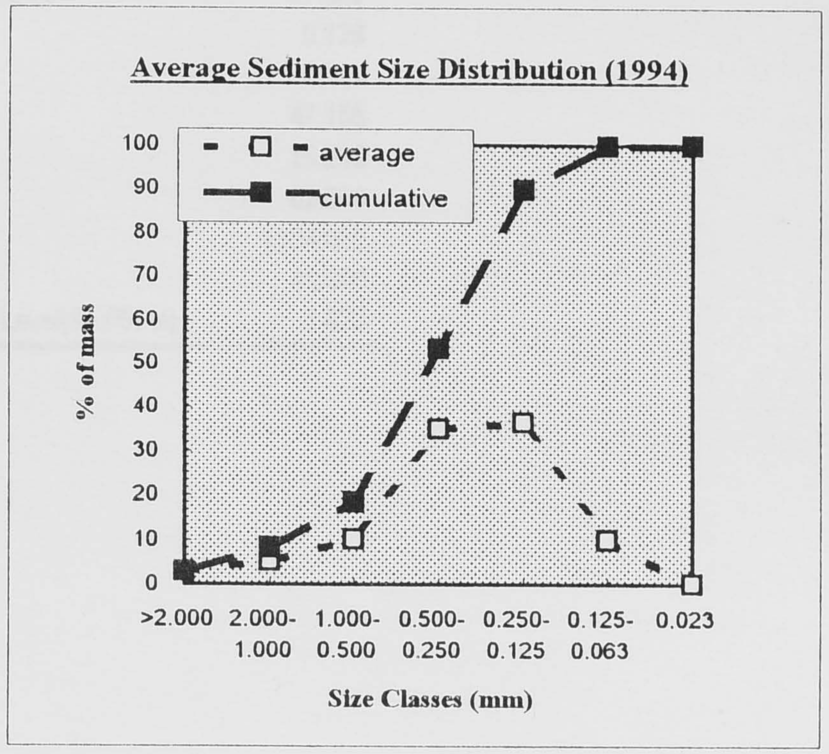
Sediment Size Distributions for 1994 Plot 3A all runs

	low												med						high					
Size\samp	A43	A44	A45	A46	A47	A48	A49	A50	A51	A52	A53	A54	A55	A56	A57	A58	A59	A60	A61	A62	A63	A64	A65	A66
>2.000	6	3	1	2	1	2	2	2	3	2	1	2	1	8	2	4	2	4	3	4	2	3	10	1
2.000-1.000	7	3	3	4	5	4	21	3	5	3	5	4	7	6	4	3	5	6	4	6	5	5	7	4
1.000-0.500	15	7	9	9	8	10	9	9	16	9	14	9	13	13	5	7	11	9	8	13	6	11	12	12
0.500-0.250	31	39	32	36	43	36	33	33	35	35	37	40	32	31	33	40	30	35	31	36	41	34	32	35
0.250-0.125	29	43	43	37	36	39	27	44	34	42	31	36	33	31	47	38	39	36	43	31	37	38	29	36
0.125-0.063	12	5	12	12	8	8	8	9	8	10	11	8	15	12	9	8	13	9	11	10	9	9	9	10
0.023	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0

Sediment Size Distributions for 1994 Plot 3B all runs

	low					med						high					
Size\samp	B24	B25	B26	B27	B28	B29	B30	B31	B32	B33	B34	B35	B36	B37	B38	B39	B40
>2.000	2	1	1	0	1	4	7	1	2	3	1	3	3	2	1	1	1
2.000-1.000	5	2	4	5	3	9	8	5	3	3	3	4	9	5	3	3	3
1.000-0.500	22	9	17	20	20	19	18	16	20	14	18	12	21	15	13	17	17
0.500-0.250	41	29	36	47	56	47	38	52	48	53	60	52	15	48	53	56	62
0.250-0.125	23	37	30	23	18	15	22	21	22	23	15	22	41	25	27	19	14
0.125-0.063	7	21	12	6	3	6	6	5	5	4	3	6	11	5	4	4	2
0.023	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

1994	% average	cumulative
>2.000	3	3
2.000-1.000	5	8
1.000-0.500	10	18
0.500-0.250	35	53
0.250-0.125	37	90
0.125-0.063	10	100
0.023	0	100



Summary Statistics of 1994 Sediment Size Distributions for Plots 3A and 3B -all runs (using Excel V5.0 Analysis tool)

>2.000		2.000-1.000		1.000-0.500		0.500-0.250	
Mean	2.475	Mean	5.018	Mean	12.929	Mean	39.854
Standard Error	0.332	Standard Error	0.475	Standard Error	0.703	Standard Error	1.542
Median	1.943	Median	4.337	Median	12.506	Median	36.446
Mode	#N/A	Mode	#N/A	Mode	#N/A	Mode	#N/A
Standard Deviation	2.129	Standard Deviation	3.042	Standard Deviation	4.503	Standard Deviation	9.876
Sample Variance	4.531	Sample Variance	9.252	Sample Variance	20.273	Sample Variance	97.530
Kurtosis	4.471	Kurtosis	17.492	Kurtosis	-0.979	Kurtosis	0.128
Skewness	1.991	Skewness	3.661	Skewness	0.289	Skewness	0.406
Range	10.273	Range	18.544	Range	16.294	Range	47.155
Minimum	0.000	Minimum	2.122	Minimum	5.283	Minimum	15.213
Maximum	10.273	Maximum	20.667	Maximum	21.577	Maximum	62.368
Sum	101.469	Sum	205.721	Sum	530.074	Sum	1634.032
Count	41.000	Count	41.000	Count	41.000	Count	41.000
Confidence Level(95.000%)	0.652	Confidence Level(95.000%)	0.931	Confidence Level(95.000%)	1.378	Confidence Level(95.000%)	3.023

0.250-0.125		0.125-0.063		0.023	
Mean	31.125	Mean	8.464	Mean	0.135
Standard Error	1.387	Standard Error	0.575	Standard Error	0.036
Median	31.269	Median	8.487	Median	0.000
Mode	#N/A	Mode	#N/A	Mode	0.000
Standard Deviation	8.882	Standard Deviation	3.680	Standard Deviation	0.231
Sample Variance	78.895	Sample Variance	13.539	Sample Variance	0.053
Kurtosis	-0.997	Kurtosis	2.220	Kurtosis	10.309
Skewness	-0.228	Skewness	0.850	Skewness	2.805
Range	32.317	Range	19.168	Range	1.193
Minimum	14.393	Minimum	2.056	Minimum	0.000
Maximum	46.710	Maximum	21.224	Maximum	1.193
Sum	1276.143	Sum	347.030	Sum	5.531
Count	41.000	Count	41.000	Count	41.000
Confidence Level(95.000%)	2.719	Confidence Level(95.000%)	1.126	Confidence Level(95.000%)	0.071

Sediment Size Distributions for 1996 Plots 2A all runs

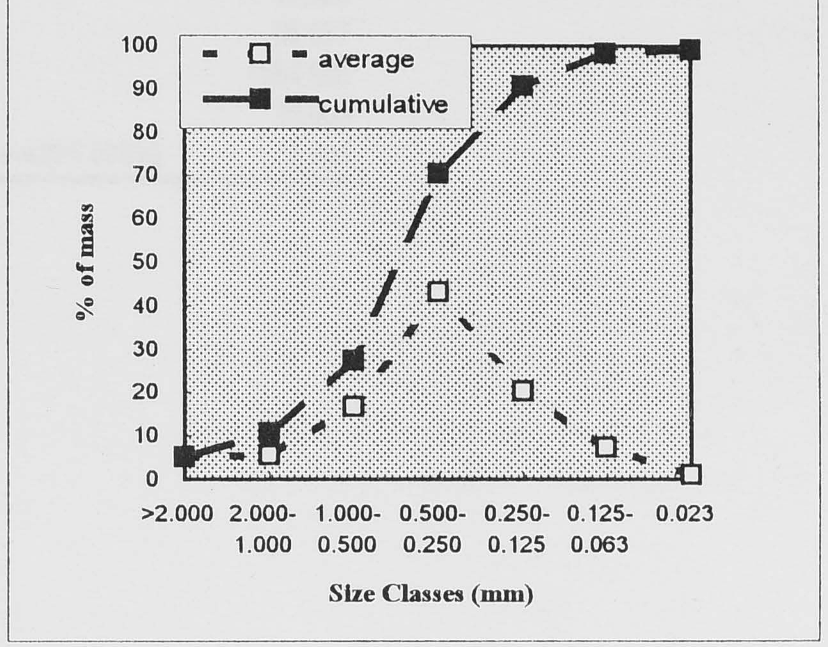
	low												med						high					
Size\samp	A20	A20	A20	A20	A20	A206	A20	A20	A20	A21	A21	A212	A213	A21	A21	A21	A21	A21	A219	A22	A22	A22	A22	A224
>2.000	8	0	17	0	0	6	0	8	0	0	7	0	5	9	7	0	0	3	5	6	0	0	0	0
2.000-1.000	12	7	17	9	0	11	0	0	7	0	14	0	0	0	0	7	0	0	0	6	0	0	8	20
1.000-0.500	12	13	11	18	17	17	19	46	13	17	7	14	21	18	53	14	7	15	15	12	17	24	8	20
0.500-0.250	31	40	33	45	67	44	63	38	53	50	43	43	53	45	13	43	40	64	45	59	58	41	54	30
0.250-0.125	19	13	17	18	17	17	13	8	20	17	21	14	11	27	20	29	33	18	25	18	25	29	23	30
0.125-0.063	15	13	6	9	0	0	6	0	7	8	7	0	5	0	7	7	20	0	10	0	0	6	8	0
0.023	4	13	0	0	0	6	0	0	0	8	0	0	5	0	0	0	0	0	0	0	0	0	0	0

Sediment Size Distributions for 1996 Plots 2B all runs

	med						high					
Size\samp	B20	B20	B20	B20	B20	B206	B20	B20	B20	B21	B21	B212
>2.000	8	0	10	0	10	14	10	0	20	20	13	0
2.000-1.000	8	10	0	0	10	0	10	0	10	0	13	20
1.000-0.500	8	20	20	29	30	14	20	12	10	0	13	0
0.500-0.250	50	40	30	43	30	29	40	37	30	40	50	40
0.250-0.125	17	20	30	29	10	29	20	37	20	40	0	0
0.125-0.063	8	10	10	0	10	14	0	12	10	0	13	40
0.023	0	0	0	0	0	0	0	0	0	0	0	0

1996	%	
	average	cumulative
>2.000	5	5
2.000-1.000	5	11
1.000-0.500	17	27
0.500-0.250	43	71
0.250-0.125	20	91
0.125-0.063	7	98
0.023	1	99

Average Sediment Size Distribution (1996)



Summary Statistics of 1996 Sediment Size Distributions for Plots 2A and 2B -all runs (using Excel V5.0 Analysis tool)

>2.000		*2.000-1.000*		*1.000-0.500*		*0.500-0.250*	
Mean	5.133	Mean	5.488	Mean	16.760	Mean	43.186
Standard Error	1.009	Standard Error	1.053	Standard Error	1.726	Standard Error	1.879
Median	4.015	Median	2.941	Median	15.076	Median	42.857
Mode	0.000	Mode	0.000	Mode	20.000	Mode	30.000
Standard Deviation	6.054	Standard Deviation	6.316	Standard Deviation	10.356	Standard Deviation	11.274
Sample Variance	36.648	Sample Variance	39.889	Sample Variance	107.250	Sample Variance	127.096
Kurtosis	0.243	Kurtosis	-0.433	Kurtosis	4.931	Kurtosis	0.430
Skewness	1.016	Skewness	0.770	Skewness	1.773	Skewness	-0.046
Range	20.000	Range	20.000	Range	53.333	Range	53.333
Minimum	0.000	Minimum	0.000	Minimum	0.000	Minimum	13.333
Maximum	20.000	Maximum	20.000	Maximum	53.333	Maximum	66.667
Sum	184.802	Sum	197.577	Sum	603.346	Sum	1554.698
Count	36.000	Count	36.000	Count	36.000	Count	36.000
Confidence Level(95.000%)	1.978	Confidence Level(95.000%)	2.063	Confidence Level(95.000%)	3.383	Confidence Level(95.000%)	3.683

0.250-0.125		*0.125-0.063*		*0.023*	
Mean	20.351	Mean	7.278	Mean	1.009
Standard Error	1.503	Standard Error	1.300	Standard Error	0.475
Median	20.000	Median	6.905	Median	0.000
Mode	16.667	Mode	0.000	Mode	0.000
Standard Deviation	9.017	Standard Deviation	7.797	Standard Deviation	2.848
Sample Variance	81.310	Sample Variance	60.794	Sample Variance	8.112
Kurtosis	0.332	Kurtosis	7.886	Kurtosis	10.538
Skewness	-0.112	Skewness	2.166	Skewness	3.177
Range	40.000	Range	40.000	Range	13.333
Minimum	0.000	Minimum	0.000	Minimum	0.000
Maximum	40.000	Maximum	40.000	Maximum	13.333
Sum	732.650	Sum	262.024	Sum	36.332
Count	36.000	Count	36.000	Count	36.000
Confidence Level(95.000%)	2.946	Confidence Level(95.000%)	2.547	Confidence Level(95.000%)	0.930

Sediment Size Distribution grouped according to Rain Intensity (both years): LOW

Size\samp	A43	A44	A45	A46	A47	A48	A49	A50	A51	A52	A53	A54	B24	B25	B26	B27	B28	A201	A202	A203	A204	A205	A206	A207	A208	A209	A210	A211	A212
>2.000	6	3	1	2	1	2	2	2	3	2	1	2	2	1	1	0	1	8	0	17	0	0	6	0	8	0	0	7	0
2.000-1.000	7	3	3	4	5	4	21	3	5	3	5	4	5	2	4	5	3	12	7	17	9	0	11	0	0	7	0	14	0
1.000-0.500	15	7	9	9	8	10	9	9	16	9	14	9	22	9	17	20	20	12	13	11	18	17	17	19	46	13	17	7	14
0.500-0.250	31	39	32	36	43	36	33	33	35	35	37	40	41	29	36	47	56	31	40	33	45	67	44	63	38	53	50	43	43
0.250-0.125	29	43	43	37	36	39	27	44	34	42	31	36	23	37	30	23	18	19	13	17	18	17	17	13	8	20	17	21	14
0.125-0.063	12	5	12	12	8	8	8	9	8	10	11	8	7	21	12	6	3	15	13	6	9	0	0	6	0	7	8	7	0
0.023	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	4	13	0	0	0	6	0	0	0	8	0	0

LOW		%
Class	average	cumulative
>2.000	3	3
2.000-1.000	6	8
1.000-0.500	14	22
0.500-0.250	41	63
0.250-0.125	26	90
0.125-0.063	8	98
0.023	1	99

Sediment Size Distribution grouped according to Rain Intensity (both years): MEDIUM

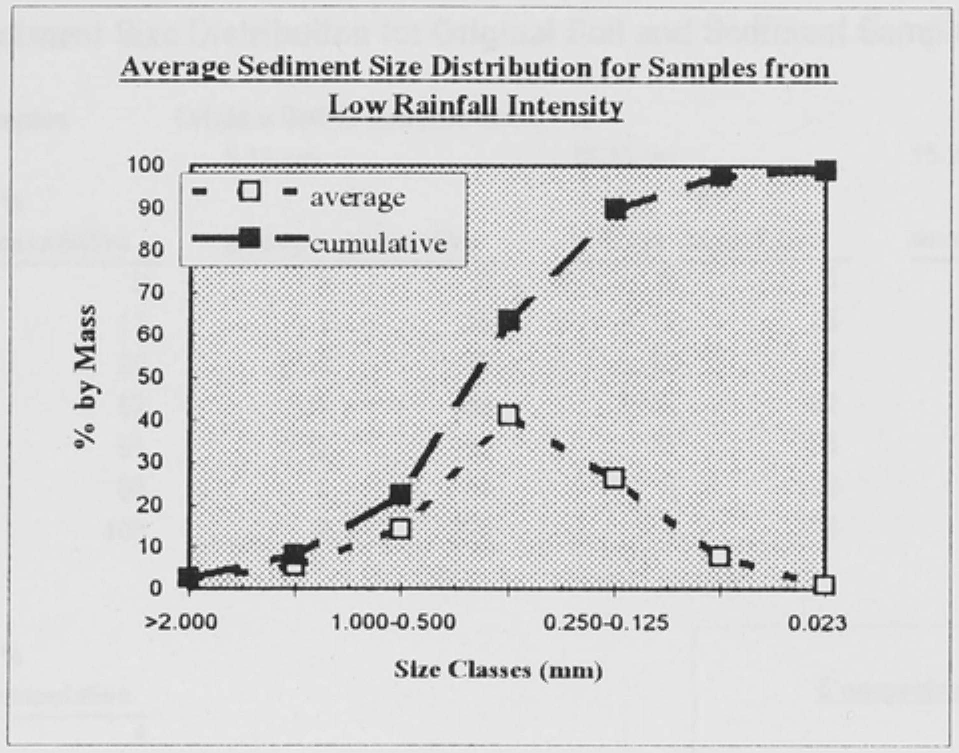
Size\samp	A55	A56	A57	A58	A59	A60	B29	B30	B31	B32	B33	B34	A213	A214	A215	A216	A217	A218	B201	B202	B203	B204	B205	B206
>2.000	1	8	2	4	2	4	4	7	1	2	3	1	5	9	7	0	0	3	8	0	10	0	10	14
2.000-1.000	7	6	4	3	5	6	9	8	5	3	3	3	0	0	0	7	0	0	8	10	0	0	10	0
1.000-0.500	13	13	5	7	11	9	19	18	16	20	14	18	21	18	53	14	7	15	8	20	20	29	30	14
0.500-0.250	32	31	33	40	30	35	47	38	52	48	53	60	53	45	13	43	40	64	50	40	30	43	30	29
0.250-0.125	33	31	47	38	39	36	15	22	21	22	23	15	11	27	20	29	33	18	17	20	30	29	10	29
0.125-0.063	15	12	9	8	13	9	6	6	5	5	4	3	5	0	7	7	20	0	8	10	10	0	10	14
0.023	0	0	0	0	0	1	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0

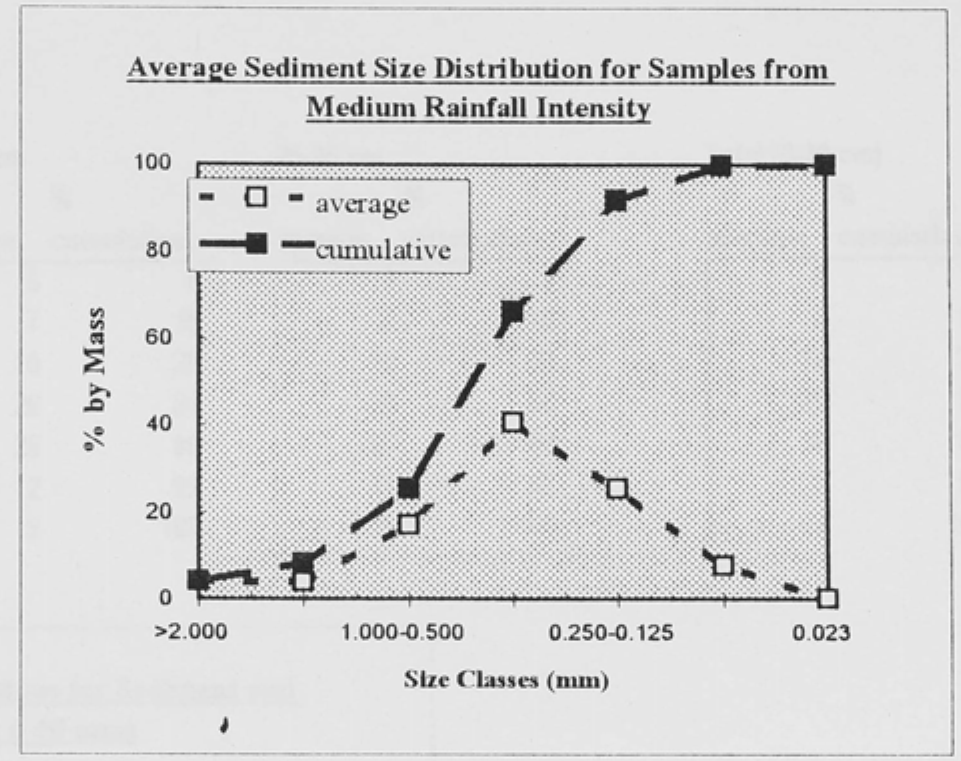
MEDIUM		%
Class	average	cumulative
>2.000	4	4
2.000-1.000	4	8
1.000-0.500	17	26
0.500-0.250	41	66
0.250-0.125	26	92
0.125-0.063	8	100
0.023	0	100

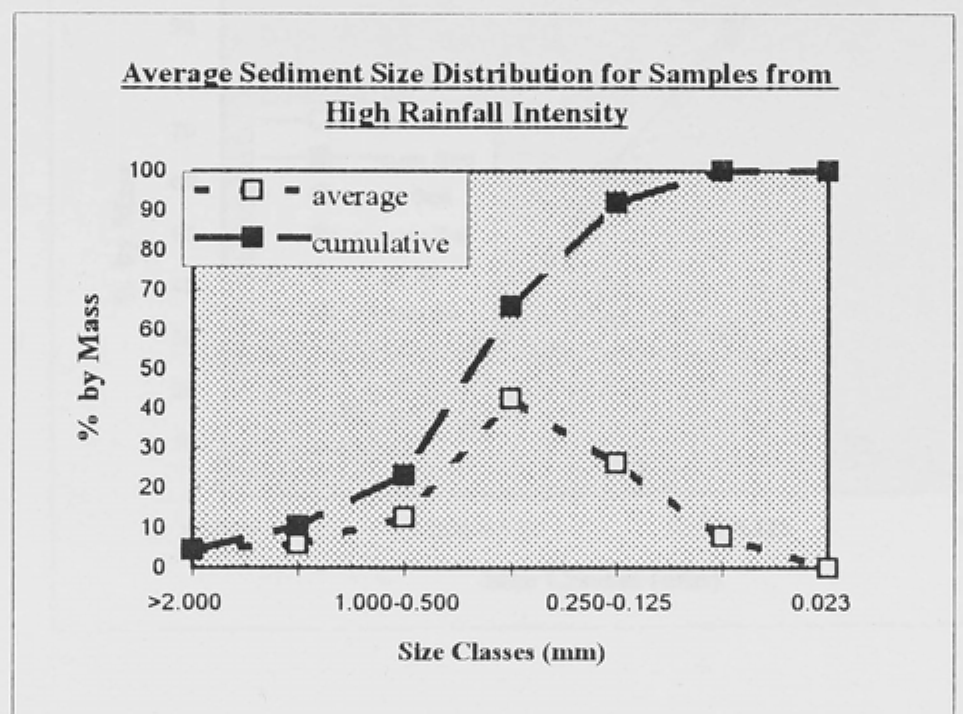
Sediment Size Distribution grouped according to Rain Intensity (both years): HIGH

Size\samp	A61	A62	A63	A64	A65	A66	B35	B36	B37	B38	B39	B40	A219	A220	A221	A222	A223	A224	B207	B208	B209	B210	B211	B212
>2.000	3	4	2	3	10	1	3	3	2	1	1	1	5	6	0	0	0	0	10	0	20	20	13	0
2.000-1.000	4	6	5	5	7	4	4	9	5	3	3	3	0	6	0	0	8	20	10	0	10	0	13	20
1.000-0.500	8	13	6	11	12	12	12	21	15	13	17	17	15	12	17	24	8	20	20	12	10	0	13	0
0.500-0.250	31	36	41	34	32	35	52	15	48	53	56	62	45	59	58	41	54	30	40	37	30	40	50	40
0.250-0.125	43	31	37	38	29	36	22	41	25	27	19	14	25	18	25	29	23	30	20	37	20	40	0	0
0.125-0.063	11	10	9	9	9	10	6	11	5	4	4	2	10	0	0	6	8	0	0	12	10	0	13	40
0.023	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MEDIUM		%
Class	average	cumulative
>2.000	4	4
2.000-1.000	6	11
1.000-0.500	13	23
0.500-0.250	43	66
0.250-0.125	26	92
0.125-0.063	8	100
0.023	0	100


Average Sediment Size Distribution for Samples from Low Rainfall Intensity
average
cumulative
% by Mass
100
90
80
70
60
50
40
30
20
10
0
>2.000
1.000-0.500
0.250-0.125
0.023
Size Classes (mm)

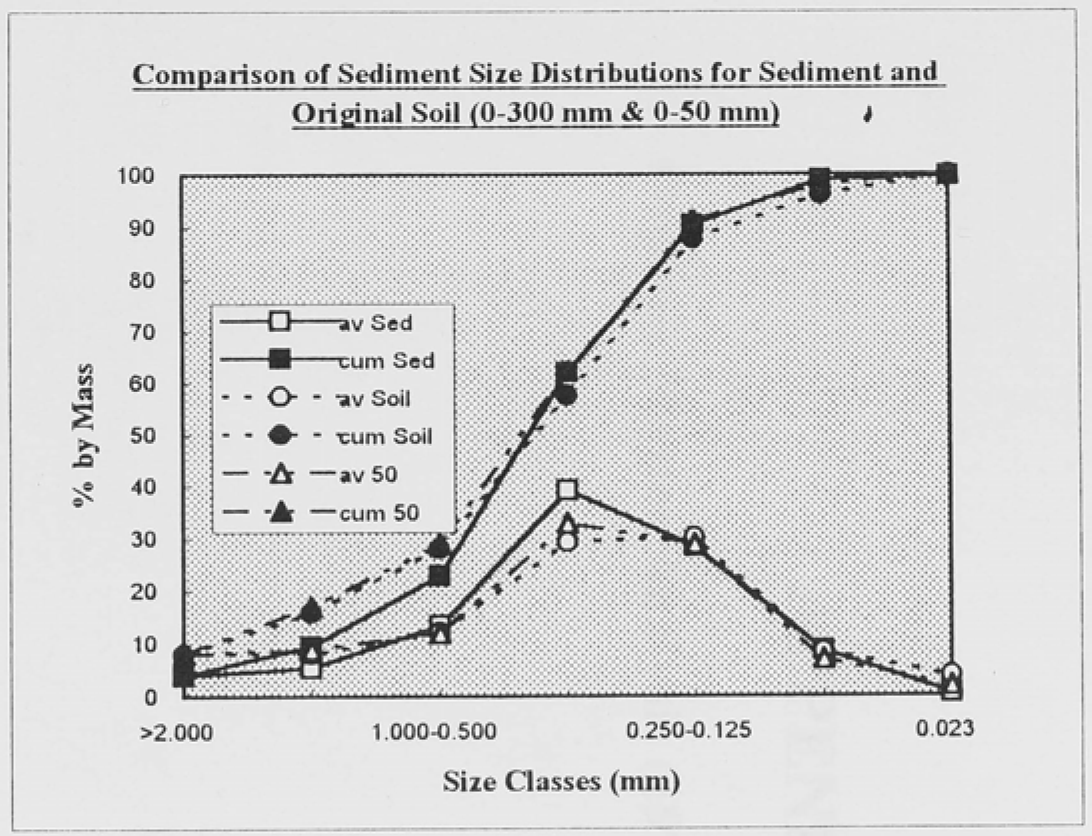

Average Sediment Size Distribution for Samples from Medium Rainfall Intensity
average
cumulative
% by Mass
100
80
60
40
20
0
>2.000
1.000-0.500
0.250-0.125
0.023
Size Classes (mm)


Average Sediment Size Distribution for Samples from High Rainfall Intensity
average
cumulative
% by Mass
100
90
80
70
60
50
40
30
20
10
0
>2.000
1.000-0.500
0.250-0.125
0.023
Size Classes (mm)

Comparison of Sediment Size Distribution for Original Soil and Sediment Samples

	All Sediment Samples		Original Soil (5 samples each)											
	0-5 cm		5-10 cm		10-15 cm		15-20 cm		20-25 cm		25-30 cm		Total (0-30 cm)	
	%		%		%		%		%		%		%	
	average	cumulative	average	cumulative	average	cumulative	average	cumulative	average	cumulative	average	cumulative	average	cumulative
>2.000	8	8	6	6	8	8	11	11	8	8	7	7	8	8
2.000-1.000	9	17	9	15	7	15	7	18	7	15	9	16	8	16
1.000-0.500	12	29	13	28	12	27	14	32	10	25	12	28	12	28
0.500-0.250	33	62	30	58	35	62	26	58	26	51	26	54	29	58
0.250-0.125	29	91	32	90	33	95	31	89	29	80	27	81	30	88
0.125-0.063	7	98	8	98	4	99	8	97	12	92	11	92	8	96
0.023	2	100	2	100	1	100	3	100	8	100	8	100	4	100

	%	
	average	cumulative
>2.000	4	4
2.000-1.000	5	9
1.000-0.500	13	23
0.500-0.250	39	62
0.250-0.125	28	90
0.125-0.063	9	99
0.023	1	100



APPENDIX V

Organic Matter Analysis (1994 only)

Organic Matter Analysis

Size\samp	A43 %Class	A43 %OM	A44 %Class	A44 %OM	A45 %Class	A45 %OM	A46 %Class	A46 %OM	A47 %Class	A47 %OM	A48 %Class	A48 %OM	A49 %Class	A49 %OM	A50 %Class	A50 %OM	A51 %Class	A51 %OM	A52 %Class	A52 %OM	A53 %Class	A53 %OM
>2.000	6	3.466	3	2.364	1	1.171	2	1.519	1	0.548	2	1.227	2	2.000	2	1.457	3	3.800	2	2.072	1	0.929
2.000-1.000	7	5.560	3	1.764	3	1.896	4	2.961	5	3.132	4	3.374	21	6.167	3	2.252	5	3.600	3	2.901	5	4.644
1.000-0.500	15	9.747	7	4.165	9	4.796	9	5.163	8	3.602	10	5.624	9	5.333	9	4.901	16	8.800	9	4.006	14	8.050
0.500-0.250	31	13.069	39	5.141	32	5.577	36	6.986	43	5.951	36	6.442	33	9.833	33	8.742	35	10.600	35	5.939	37	8.669
0.250-0.125	29	8.375	43	3.452	43	5.466	37	5.847	36	3.367	39	4.499	27	6.667	44	5.430	34	6.200	42	3.729	31	7.740
0.125-0.063	12	3.755	5	1.051	12	6.135	12	1.670	8	1.253	8	1.329	8	2.167	9	1.457	8	0.800	10	0.967	11	4.644
0.023	0		0		0		0		0		0		0		0		0	0.000	0		1	0.000

Size\samp	A54 %Class	A54 %OM	A55 %Class	A55 %OM	A56 %Class	A56 %OM	A57 %Class	A57 %OM	A58 %Class	A58 %OM	A59 %Class	A59 %OM	A60 %Class	A60 %OM	A61 %Class	A61 %OM	A62 %Class	A62 %OM	A63 %Class	A63 %OM	A64 %Class	A64 %OM
>2.000	2	1.452	1	0.780	8	7.965	2	1.668	4	1.799	2	0.942	4	1.392	3	3.223	4	4.423	2	1.063	3	2.740
2.000-1.000	4	3.226	7	4.971	6	5.015	4	2.224	3	2.608	5	3.766	6	5.169	4	3.581	6	4.791	5	2.481	5	2.226
1.000-0.500	9	4.839	13	7.407	13	7.375	5	2.780	7	3.777	11	4.708	9	6.561	8	4.387	13	6.511	6	2.622	11	6.678
0.500-0.250	40	5.968	32	8.090	31	7.375	33	4.541	40	4.227	30	4.331	35	6.362	31	4.655	36	5.528	41	3.260	34	7.363
0.250-0.125	36	3.548	33	5.361	31	6.490	47	3.336	38	3.058	39	3.578	36	3.579	43	4.655	31	3.563	37	2.977	38	6.164
0.125-0.063	8	1.290	15	3.606	12	3.097	9	1.483	8	1.709	13	1.883	9	2.187	11	2.507	10	2.826	9	2.268	9	2.740
0.023	0		0		0		0		0		0		1	0	0		0		0		0	

Size\samp	A65 %Class	A65 %OM	A66 %Class	A66 %OM	B24 %Class	B24 %OM	B25 %Class	B25 %OM	B26 %Class	B26 %OM	B27 %Class	B27 %OM	B28 %Class	B28 %OM	B29 %Class	B29 %OM	B30 %Class	B30 %OM	B31 %Class	B31 %OM	B32 %Class	B32 %OM
>2.000	10	9.791	1	1.325	2	1.037	1	0.000	1	0.799	0		1	0.544	4	3.101	7	4.645	1	0.331	2	0.069
2.000-1.000	7	5.136	4	3.735	5	3.112	2	0.740	4	2.078	5	2.807	3	2.085	9	5.290	8	4.372	5	2.581	3	2.132
1.000-0.500	12	6.581	12	5.663	22	8.195	9	1.135	17	6.340	20	7.982	20	6.800	19	7.798	18	6.940	16	5.228	20	4.539
0.500-0.250	32	6.260	35	3.373	41	0.000	29	2.912	36	8.791	47	0.000	56	0.000	47	0.000	38	9.563	52	8.736	48	6.671
0.250-0.125	29	4.173	36	3.614	23	6.846	37	4.886	30	4.209	23	6.228	18	6.437	15	5.837	22	6.776	21	6.023	22	4.883
0.125-0.063	9	2.247	10	2.289	7	2.075	21	2.912	12	1.545	6	1.228	3	0.997	6	1.824	6	1.858	5	0.860	5	1.651
0.023	0		0		0		0		0		0		0		0		0		0		0	

Size\samp	B33 %Class	B33 %OM	B34 %Class	B34 %OM	B35 %Class	B35 %OM	B36 %Class	B36 %OM	B37 %Class	B37 %OM	B38 %Class	B38 %OM	B39 %Class	B39 %OM	B40 %Class	B40 %OM
>2.000	3	2.558	1	0.000	3	2.226	3	0.746	2	1.149	1	0.673	1	0.756	1	1.121
2.000-1.000	3	1.762	3	1.687	4	2.295	9	4.623	5	2.573	3	1.972	3	1.134	3	1.869
1.000-0.500	14	4.264	18	4.521	12	3.904	21	7.383	15	4.379	13	2.934	17	2.916	17	3.053
0.500-0.250	53	5.458	60	5.601	52	5.548	15	0.000	48	5.638	53	5.099	56	4.212	62	4.548
0.250-0.125	23	4.434	15	1.822	22	3.356	41	4.773	25	3.831	27	2.934	19	2.484	14	2.368
0.125-0.063	4	1.023	3	0.405	6	1.267	11	7.905	5	1.095	4	1.154	4	1.080	2	0.062
0.023	0		0		0		0		0		0		0		0	

Size Class	average%	average OM%
>2.000	4	1.924
2.000-1.000	5	3.178
1.000-0.500	13	5.424
0.500-0.250	39	6.991
0.250-0.125	28	4.707
0.125-0.063	9	2.056
0.023	1	0.000

APPENDIX VI

Publication in the Australian Journal of Soil and Water Conservation

Zierholz, C., Hairsine, P.B. and Booker, F.A. **(1995)**
Runoff and soil erosion in bushland following the Sydney bushfires.
Australian Journal of Soil and Water Conservation **8**: 28-36.

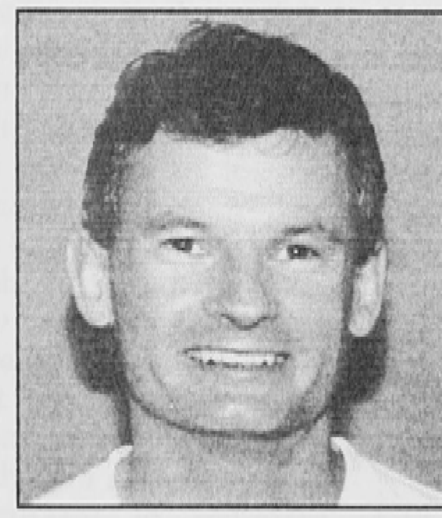
RESEARCH

Investigating data on soil losses occurring in the aftermath of bushfires, with particular emphasis on vegetation effects and the role of soil water — repellence.

RUNOFF AND SOIL EROSION IN BUSHLAND FOLLOWING THE SYDNEY BUSHFIRES

CHRISTOPH ZIERHOLZ — CSIRO Division of Water Resources, Canberra, Australian Capital Territory.

PETER HAIRSINE — CSIRO Division of Soils, Canberra, Australian Capital Territory.



Co-author — FRED BOOKER, University of California, Berkeley, U.S.A.

Abstract

This article reviews the findings of previous studies on runoff and erosion in overseas ecosystems similar to those affected by the January 1994 fires around Sydney, N.S.W. Relevant studies in Australia are also examined. Observations of changes in rates of soil erosion and overland flow generation in the north-eastern part of Royal National Park are described. Effects on infiltration and formation of water-repellence or 'hydrophobicity' are reported. The role of soil cover by plants and litter mulch during the regenerative phase in protecting the soil against raindrop impact and flow-driven erosion is described.

Key Words: Fires, soil erosion, runoff, water-repellence, ground cover, revegetation.

The January 1994 bushfires brought devastation to the lives, property and environment of the people of New South Wales. Following the fires, there are several environmental consequences which may further impact on the community. Increased runoff and soil erosion are two of these potential consequences. This article reviews the findings of overseas researchers and reports on observations of runoff and soil erosion in the near-natural fringe around Sydney following the January 1994 fires. Emphasis is placed on the interaction between natural processes and man-made structures. The eastern portion of Royal National Park is used as a specific example where a near-natural system has experienced some land degradation as a result of such interaction.

Bushfires are a natural part of much of the Australian landscape. While the frequency and magnitude of fires have been modified by land use (Luke and McArthur, 1978; Gill, 1981; Nicholson, 1981; Walker *et al.*, 1986), most natural and near-natural areas retain some adaptation to bushfires. Bushfires have been found to change the way water moves through landscapes similar to that affected by the January 1994 fires in several studies, e.g., South Africa, Spain, United States. In natural systems, this is a part of ecosystem and landscape development. On managed land this change in hydrology may result in environmental problems which may or may not justify further management.

OVERSEAS RESEARCH

There are several regions overseas that support similar ecosystems to those affected by the January 1994 fires. These landscapes have developed with fire having a major role in their evolution process. The vegetation types endemic to such areas are mostly sclerophyllous shrublands and forests adapted to fire. Under natural conditions, such landscapes suffer no degradation from burning.

In many cases, these areas have not been changed extensively as their suitability for grazing, agriculture or development is poor. The main land use in these regions have been grazing, water harvesting and forestry (South Africa). Human population pressures have resulted in additional use for recreation and urban development (California). The increase in use and development has led to a rise in perceived value and the need to manage these areas as resources. Knowledge of the effects of fire on the land use of these ecosystems is important if we are to prevent degradation.

The Californian Fires

With the continued expansion of the urban environment into the highly flammable bushlands of California, the potential for large destructive fires is increasing, as is the potential for catastrophic erosional response. In southern California there have been a hundred such fires in the last 37 years. In these locations, the urban environment is situated in an area of active tectonism, where rapid uplift of surrounding mountain ranges results in steep and extensively fractured slopes (30 to 60 degree slopes), where background erosion rates can be in the order of 1.4 mm to 2.3 mm per year (Wells, 1981; Scott and Williams, 1978). Following fires, much of this loose soil and colluvium moves downslope and accumulates in channels in a gravity driven process called ravel. Increased runoff following fires transports much of this material out of the catchment. This post-fire landscape response in steep burned canyon-lands is called a fire-flood sequence (USDA, 1954). Typically, autumn wildfires are followed by winter flood events. These floods can transport large amounts of soil and debris (ravel), prompting some researchers to classify them as debris and mud flows (Wells, 1987).

Changes in the runoff hydrograph following catchment burning are attributed primarily to the development of hydrophobic soils (Wells, 1987). Loss of interception and storage provided by plants and organic litter also contribute to this change in catchment response. Soil hydrophobicity can occur naturally in unburned catchments in association with some vegetation types and change in seasonal behaviour (Debano, 1981; Crockford *et al.*, 1991; Booker *et al.*, 1993). Fire-induced hydrophobicity, especially in the chaparral covered slopes of coastal southern California, can produce significant changes in soil hydrology following burning (Debano, 1981; Savage, 1974; Wells, 1981). As a result, fire-induced changes in runoff can have a major impact on the downstream urban environment, further complicating post-fire recovery.

This process of fire-flood response particular to southern California has been applied to other landscapes in California as a model of landscape response following fires, most recently after a large urban-bush fire in Oakland, California in 1991 (and by the same American consultants following the Sydney fires). In Oakland, the identification of hydrophobic soils and an estimated erosion potential of 142 m^3/ha- led to the implementation of a massive erosion control project that totalled almost US$ 5 million. Burned bushland slopes were initially aerial-seeded with grasses and then reseeded as part of a hydromulch application of organic fibres and a copolymer glue. Areas prone to landslides and channels were also treated with straw-bale-check-dams to moderate overland flow and to store sediment (Booker *et al.*, 1993).

The fire-flood model of landscape response and post fire erosion control effectiveness were tested by a group of researchers at the University of California at Berkeley (Booker *et al.*, 1993). They found that in the Oakland hills, although some hydrophobicity was present, there was not a continuous water-repellent layer. There were sufficient vertical flow paths for infiltration of water that fell in rain events that occurred. Persistent overland flow did not develop except in discrete areas that generated runoff such as roads, trails and bedrock outcrops. The majority of soil loss occurred early in the winter before germination of the seeded grasses and rates of erosion declined rapidly as the winter progressed. These researchers also found that straw-bale-check-dams were largely ineffective as they could not withstand flows greater than 0.03 m^3/s and that bales would begin to decay within three months of installation releasing stored sediments. The use of hydromulch, although costly, was effective in reducing runoff and erosion. Hydromulching was however not needed in the Oakland hills fire area, as soil cohesion and natural revegetation of native plants was sufficient in limiting erosion on undisturbed slopes. Total sediment loss on untreated and burned bushland slopes was in the order of 1 m^3/ha several orders of magnitude less than the estimated soil loss of 142 m^3/ha (which is comparable to soil loss rates following fires in some southern California areas). Rainstorm intensities that produced debris and mud flows following the 1993 fires in some southern California communities did not result in the predicted response following the Oakland fire in 1991.

Research in South Africa

The effects of wildfire and prescribed burning on catchment hydrology have also been studied in South African ecosystems ranging from fynbos associations (the indigenous shrub vegetation of the south-western Cape, South Africa) to *Pinus* and *Eucalyptus* plantations (De Ronde, 1990; Scott and Van Wyk, 1990; Scott, 1993).

All researchers observed significant increases in runoff and soil loss following major fires. Scott and Van Wyk (1990) concluded that "...the widespread development of water-repellence in the soil led to overland flow during larger rainstorms, which in turn caused the markedly altered hydrological behaviour of the catchment and the high soil losses relative to the unburned condition". In this study, it was found that while weekly stream flow totals increased by 12 per cent, quick flow volumes and peak flow rates increased by 201 per cent and 290 per cent respectively, indicating a 'biased' effect toward larger rainstorms in catchment response.

Increases in sediment yield from undisturbed fynbos catchments were orders of magnitude less than those recorded from plantation forests impacted by forestry operations. The difference in soil loss was attributed in part to differences in burn intensity; the plantations were affected by hot wildfire while the fynbos was subjected to a prescribed (low intensity) burn. Scott and Van Wyk (1990) also observed concentration of overland flow on compacted logging paths.

In a further study, Scott (1993) reported fire-induced increases in peak discharge of 1110 per cent and in quick flow of 92 per cent for a *Eucalyptus* catchment. As with the earlier study, changes in storm flow behaviour were attributed to changes in soil hydrological character and alteration in vegetative cover. Skid paths and roads were observed to deliver overland flows and eroded sediment rapidly and efficiently.

In both studies, the role of roads and similar disturbed areas were seen as exacerbating the problem of runoff and soil erosion, caused by the effects of fire.

Studies in Spain

The transition from a burned area to a relatively stable soil environment is the study reported by Diaz-Fierros *et al.* (1987). In this study, soil erosion was measured following a major wildfire in the forest region of north-west Spain. It was found that the major erosion in this area happened soon after the fires when there was little vegetative cover to protect the soil surface. Erosion rates then declined rapidly as the vegetation recovered.

Similarly, May (1990) reported considerable increase of surface runoff following several fires in a catchment in southern Spain. The most intense fire resulted in considerable increase in surface runoff which declined as the vegetation regenerated. The hydrological behaviour of the catchment reverted to pre-fire condition within three to four years despite seemingly unfavourable conditions for regeneration. Two smaller fires in the same catchment resulted in no detectable increase in surface runoff. This was attributed to local variations in vegetation, topography and the size and intensity of the fires.

Belillas and Rodà (1993) describe observations after prescribed burning of dry heathland in north-eastern Spain. They recorded increased annual streamflow of at least 36 per cent which again, only persisted for two years after burning before returning to pre-fire conditions. The effects of particulate matter and dissolved nutrients on streamwater quality were found to be negligible. Nutrients released by the ash were adsorbed and retained efficiently by the soil.

These studies illustrate the response of relatively undisturbed fire-adapted ecosystems to burning.

Summary of Overseas Research

Fire is followed by increased erosion but this effect is variable; depending on a range of environmental factors. A common pattern found has been an initial flush of sediment, usually in the first major runoff-producing rainstorm event, followed by declining soil loss which tends to return to what may be called the background erosion rate after several years. This recovery period may vary depending on the type of environment (vegetation, soils, geology, geomorphology) represented by the burned area.

The initial large flush of sediment observed after fire in these and other studies may represent several sources or combinations of sources: ash, charcoal and remaining (unburned) litter, existing sediment or loose soil and/or soil detached from the soil surface. The southern Californian fire-flood sequence represents an extreme case of such existing deposits being mobilised as a result of fire. The accumulation of debris and sediment in waterways is part of the ongoing landscape formation process and occurs independently of fire. Erosion mitigation works following the Oakland fires were only partly successful, despite high investment. Sediment control measures designed for construction sites were unnecessarily applied to undisturbed burned areas.

The studies indicate that the natural landscape response to fire in undisturbed areas is generally adequate in protecting the ecosystem from degradation beyond a natural level. Disturbed areas are prone to accelerated degradation, as these sites are unable to cope with the increased levels of runoff produced during the recovery period. It appears from these studies that the greatest risk of detrimental erosion is associated with disturbances of the landscape system, the most significant process involved being the concentration and channelling of runoff.

AUSTRALIAN RESEARCH

In the Australian landscape, the native vegetation has evolved with a long history of fire (Gill *et al.*, 1981). Australian Aborigines and later European settlers have been using fire extensively as a land management tool. Much of the research related to fire-induced erosion in Australia has been in the field of forest hydrology (Mackay and Cornish, 1982; O'Loughlin *et al.*, 1982; Kuczera, 1985; Wilson, 1993) and rangeland management (Chartres and Mücher, 1989; Greene *et al.*, 1990; Kinnell *et al.*, 1990). In general, the findings of the Australian research is similar to those of the overseas scientists.

It is difficult to transfer research findings because the areas around Sydney which were affected by the January 1994 fires differ markedly in soil type, vegetation and landscape characteristics from other areas studied in Australia. Comparisons should therefore be based on general geomorphological and hydrological behaviour rather than site specific inference.

Generally, burned and disturbed sites are more prone to accelerated erosion and consequent further degradation on and off-site than are burned but otherwise undisturbed areas. Disturbed sites may be in the form of bulldozed firebreaks, existing fire-trails or areas of reconstruction (especially in urban areas). Increases in total runoff, peak

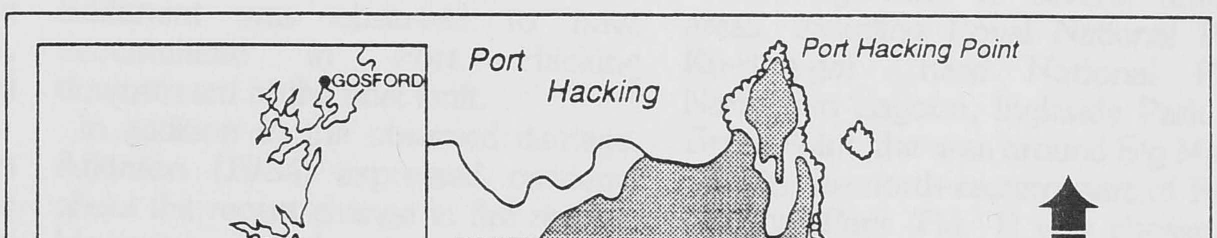


Figure 1. Map showing the locality and geological attributes of the study area.